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ON

BEARING LUBRICANT ENDURANCE CHARACTERISTICS AT HIGH SPEEDS AND HIGH TEMPERATURES

PERIOD: January 1, 1965, through March 31, 1965

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SKF INDUSTRIES, INC.

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BEARING LUBRICANT ENDURANCE CHARACTERISTICS AT HIGH SPEEDS AND HIGH TEMPERATURES

INTRODUCTION

This is the tenth quarterly progress report on research performed under Contract NASw-492, "A Study of Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures."

Research is being undertaken in two phases:

a. In Phase I, the limiting load, speed and temperature of high-temperature tool-steel ball bearings (7205-size) lubricated with the most advanced present-day fluids are being evaluated.

b. In Phase II, optimum bearing-lubricant combinations are being endurance tested in 30-bearing groups at the predetermined test conditions in order to establish their design life and reliability parameters.

Tests are conducted in high-speed high-temperature test machines developed by SKF Industries, Inc., in a nitrogen-blanketed environment (except for some tests in which the effect of air environment is studied).

CONCLUSIONS

1. Ester-base lubricants, such as Esso Turbo Oil 35 and Sinclair Turbo S lubricate M-1 tool steel bearings quite satisfactorily at high speeds and temperatures up to 500°F, under which conditions about half the AFBMA computed life can be obtained.

2. Monsanto Skylube 600 polyphenyl ether did not lubricate the M-1 bearings well under any of the test conditions used, due to a large number of smearing failures shortly after start-up in these high-speed tests. Initial testing with Monsanto MCS-293 and OS-138 polyphenyl ethers indicate that these lubricants may be superior to the Skylube 600.

3. Socony Mobil XRM 109F-1 hydrocarbon gave unsatisfactory performance (about 1% of computed life) at 600°F, presumably due to its inability to prevent smearing in these high-speed tests (42,800 rpm). The effect of bearing groove roughness and anti-wear additives on bearing performance is being explored.

SUMMARY

1. Phase I Testing

(a) Longer bearing life was obtained during this report period with polyphenyl ether type lubricants than in any previous polyphenyl ether tests. Monsanto MCS-293 (a modified polyphenyl ether having -20°F pour point) operated in one test at 500°F, 42,800 rpm, and 365 lbs. load for 58.5 mill. revs. without surface distress. This performance is considerably better than anticipated on the basis of the critical oil film thickness computed from previous test results with the more viscous 5-ring and 6-ring lubricants. The 6-ring fluid, Monsanto OS-138, operated in another test at 598°F for 50.3 mill. revs. with only slight glazing of the inner-ring ball track.

Two of four tests with the 5-ring Monsanto Skylube 600 lubricant in an air environment survived for appreciable lives, which may refect an improved boundary lubricating characteristic of this oxidation-resistant fluid in an oxidizing atmosphere. In one of the tests in air, with 459 lbs. load, the Skylube 600 operated at 572°F for 189.3 mill. revs., with only slight glazing of the raceways. This contrasts with 13 early failures out of 16 with Skylube 600 in N_2 atmosphere (to be discussed later).

(b) A single test was conducted at 580 lbs. load with CVM M-1 bearings and the ester-base lubricant, Esso Turbo Oil 35, at 500°F, to establish the limiting load for this bearing-lubricant combination. One bearing smeared after 115.3 mill. revs. at 500°F, while the other bearing operated for the same life at 484°F without surface distress, indicating that the safe operating temperature is below 500°F at this high load (lower load tests will be described below).

Sinclair Turbo S ester-base lubricant operated at 365 lbs. load for 230 mill. revs. in one test at 550°F, with only slight glazing, thus demonstrating at least as much maximum temperature capability as Turbo Oil 35.

(c) Two M-1 bearings operated satisfactorily with Kendex Bright Stock 0846 mineral oil at 490° to 570°F, under 459 lbs. load for 231 mill. revs., indicating that this lubricant may have as much maximum temperature capability as Socony Mobil XRM 109F-1 hydrocarbon, in which Phase II endurance tests are being run.

2. Phase II Endurance Testing

Results of endurance testing at 42,800 rpm completed during this report period on three complete groups of statistically similar 7205 bearings made of CVM M-1 steel and started on three other smaller groups, together with the maximum likelihood estimated life parameters for each group (where available), are summarized below.

						Brg. L_{10} Life, Mill. Revs.		
Lubricant	Avg. Temp. °F	Thrust Load Lbs.	No. Brgs. Tested	No. Smearing and Flaking Failures	Total No. Failures	AFBMA	Est. From Smearing and Flaking Failures	Est. Total Failures
Turbo Oil 35	500	365	30	2	8	480	247.7	116.9
Turbo Oil 35	500	459	30	10	13	240	58.8	47.7
Skylube 600	595	459	22	11	13	240	*	*
Skylube 600	481	365	6	3	3	480	*	*
Skylube 600**	600	459	8	4	4	240	*	*
XRM 109F-1	600	459	10	3	5	240	3.17	2.03

* No valid life estimates were obtained since most failures occurred shortly after start-up.

**These tests were run in an air environment, all others with N_2 blanketing.

These results show that about half the AFBMA computed L_{10} life of these bearings can be obtained at 500°F with Turbo Oil 35 under 365 lbs. load, but at 459 lbs. load, less than 1/4 of the computed life is realized. Numerous failures shortly after start-up with Skylube 600 are attributed to the poor boundary lubricating properties of this fluid. The possibility that ball skidding in ring grooves having very smooth surface finish may contribute to smearing failures will be investigated. The very low preliminary life estimates with XRM 109F-1 are contrary to previous Phase I test results and may also result from ball skidding effects, since this oil does not contain anti-wear additives. The possibility of running further tests with an XRM 109F-1 oil having an anti-wear additive is being studied.

DETAILS

The bearings tested during this report period were constructed with CVM M-1 tool steel races and balls, and silver-plated hardened (Rc 55) M-1 steel cages shown in Enclosure 16 of (1)*. Their inner-race grooves were specially honed to a surface finish across the groove of 3-5 microinches, rms, and their ground and polished outer-ring grooves measured 6-8 microinches, rms. The unmounted radial looseness of the bearings ranged from 35-53 microns and the average radial cage play, from .0050" to .0095". Dimensions of each individual bearing before test are given in Enclosure 1. In all tests, both rings of the bearings had been black-oxide coated in order to reduce the chance of surface distress from occurring during start-up.

The temperature-viscosity characteristics of the lubricants used are shown in Enclosure 2. In these tests, at 42,800 rpm, circulating oil flow to the bearings was maintained in the order of 600 cc/min. to each bearing. Oil sump capacity is 1000 cc per bearing. New oil was added periodically throughout each test to replace fluid lost by decomposition and evaporation out the labyrinth seals in the test machines. A small flow rate of N_2 gas was supplied both to the sump and to the test bearing cavity as an inert blanket to reduce oil decomposition, except in special tests when air was used as the blanketing gas.

In order to increase the dissipation of the heat generated in the bearing housing block and provide satisfactory control of the bearing operating temperature using 15-20% of the heater capacity, two cooling fans, one on each side of the machine, were employed. No oil cooling was used.

1. Phase I Testing

A summary of the test results obtained during this report period is given in Enclosure 3.

A modified polyphenyl ether type fluid, Monsanto's MCS 293, was used to lubricate the bearings in Test Run #56,

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* Numbers in parentheses refer to References at the end of this report.

which was conducted at mean temperatures up to 516°F (oil viscosity = 0.73 cs), 42,800 rpm, and under 365 lbs. thrust load (AFBMA computed L_{10} life = 480 mill. revs.). During the initial 11 hours of the test, the bearings were run at mean temperatures up to 500°F (oil viscosity = 0.76 cs), and thereafter their temperatures were increased up to 550°F (extrapolated oil viscosity = 0.66 cs) to check performance at the higher temperature since satisfactory ester-type lubricants are available for 500°F operation. Examination of the bearings after 22.8 hours (58.5 mill. revs.) indicated that the load-end bearing had glazed and flaked. Its cage had split in two (all cage bars were broken) even though its bore wear was less than 0.1 mils (Enclosure 4). The drive-end bearing was in good condition as shown in Enclosure 5. Its cage-bore wear was also less than 0.1 mils, which is not considered significant.

In Test Run #57, the bearings were lubricated with a high-viscosity ester-base oil, Sinclair Turbo S (type 1048, improved), at 42,800 rpm, mean temperatures up to 550°F (extrapolated oil viscosity = 1.26 cs) under 365 lbs. thrust load. The test was terminated after 230.0 mill. revs., when the load-end bearing temperature increased rapidly. Examination of the bearings indicated that the load-end bearing had smeared and its cage and balls had shattered (Enclosure 6). The drive-end bearing was slightly glazed and its cage-bore wear was 1.0 mils (Enclosure 7).

Since extremely short duration tests were experienced in endurance tests (Phase II) conducted with Monsanto Skylube 600 (PWA 524), which are described later in this report, a check-out run under identical endurance-test conditions was conducted with Kendex Bright Stock 0846 oil, lubricating the bearings in Test Run #58. The test conditions were set at 42,800 rpm, mean temperatures up to 571°F (extrapolated oil viscosity = 1.60 cs). Both bearings operated satisfactorily until their time-up life of 231.1 mill. revs. and, as shown in Enclosures 8 and 9, were in good condition with a corresponding cage bore wear of less than 0.1 mils.

A six-ring polyphenyl ether, Monsanto OS-138 (MLO-60-231), was used to lubricate the bearings in Test Run #59, which was conducted at 42,800 rpm, mean temperatures up to 598°F (extrapolated oil viscosity = 1.16 cs) and under 365 lbs. thrust load.

As done in the previous test with this lubricant (and in previous tests with Monsanto OS-124 which does not have the inhibitors present in Skylube 600), copper inhibitors (in the form of sheets and screening) were placed in each oil sump. Since static compatibility tests have shown that the standard asbestos-type gaskets used at the various fittings and mated surfaces in the machine, such as between the oil sump and housing block, lose strength by leaching and possibly contaminate the high-temperature polyphenyl ether, special attempts were made to find better gasket material in order to maintain a very clean system for this test (even though these gaskets are exposed to the oil only at their edges and there has been no evidence of excessive decomposition of the asbestos gaskets in polyphenyl ether lubricated rig tests). A gasket material which is known to be compatible with polyphenyl ether, Du Pont polyimide type SP-1 plastic, was procured and used for the first time in this test. In addition, the machine was made exceptionally clean prior to start-up. Excessive wear on the inner-race lands of the load-end bearing resulted in termination of the test after 50.3 mill. revs. Examination of the bearings indicated that the load-end bearing was glazed and fragment dented; whereas, the drive-end bearing rings were only slightly glazed. The cage bore wear was 1.0 and 9.2 mils for the drive-end and load-end bearings, respectively (Enclosures 10 and 11).

Discussion of Phase I Test Results

Based on the results obtained with Monsanto's modified polyphenyl ether, MCS 293, in Test Run #56, it appears that this lubricant is capable of satisfactorily lubricating the bearings at least for 11 hours at temperatures up to 500°F, which is surprising since its viscosity at this temperature is only 0.76 cs. Previous test results with OS-124 and PWA 524 polyphenyl ethers indicated that excessive glazing, leading to premature flaking failures, occurred at temperatures corresponding to viscosities below about 1.2 cs. The performance of MCS 293 at temperatures up to 550°F (0.66 cs) did seem to deteriorate, as evidenced by the condition of one of the two test bearings at the termination of this test.

The CVM M-1 steel bearing-Turbo S oil combination performed quite satisfactorily in Test Run #57, since the bearings operated for 230 mill. revs. at mean temperatures up to 550°F before failure occurred. These results indicate that the Turbo S oil gives just as good, possibly better, high-temperature performance as the previously most promising ester-base oil, Turbo 35, which has given fairly consistent glazing-free performance in these bearings at 500°F. Some improvement in the maximum temperature capability of the Turbo S oil over Turbo Oil 35 is expected on the basis of its slightly greater viscosity.

The excellent condition of the bearings in Test Run #58 after running to the time-up life of 231.1 mill. revs. at mean temperatures up to 571°F indicates that the Kendex Bright Stock 0846 oil also should be considered for future endurance testing. These results confirm previous Phase I test experience with this mineral oil, indicating a maximum safe temperature of 600°F for glazing-free operation in an inert environment.

Both bearings in Test Run #59, which was conducted with Monsanto's 6-ring polyphenyl ether, OS-138, at mean temperatures up to 598°F, exhibited some surface distress after 50.3 mill. revs. It is felt that these bearings could have operated longer had not the silver plating worn off the cage bore of one bearing and excessively grooved its inner-race land surface. Since there was no evidence of any rig malfunctioning in this test, it is assumed that this cage wear resulted from the poor boundary lubricating characteristics of the lubricant. Among the tests conducted with polyphenyl ether type lubricants, this test was second in life only to Test Run #56, which was conducted at a lower mean temperature (516°F) with Monsanto MCS 293.

Lubrication of Cage Bore Guide Surfaces - Phase I Testing

The silver-plated hardened (Rc 55) M-1 steel cages shown in Enclosure 16 of (1) have worn negligibly in recent tests. Of the eight cages run in Phase I bearings during this report period, four wore less than 0.1 mils, two had slight wear of 0.8 to 1.0 mils, and one of the remaining two shattered while the other wore 9.2 mils. The cage in Bearing No. 284, Run #57 shattered. This is attributed to the fact that the bearing smeared. Excessive wear developed in the bore of the cage for Bearing No. 325, Run #59, for unknown reasons.

2. Phase II Endurance Testing

The following groups of 7205-size bearings were endurance tested under thrust load at 42,800 rpm until failure or until a time-up life of 90 hours (231.1 mill. revs.), whichever occurred first.

CVM M-1 Bearings at 500°F With Turbo Oil 35 Under 365 lbs. Load

Testing of the remaining 16 bearings of the first group of thirty-two CVM M-1 steel bearings on which endurance testing was started previously (1) with Esso Turbo Oil 35 at 500°F 42,800 rpm and 365 lbs. thrust load (C/P = 7.8) was completed during this report period, and a summary of the overall results of this group are given in Enclosure 12. All bearings tested in this report period were fitted with hardened M-1 cages having silver plating on the cage bore guide surfaces (some previously tested bearings in this group had S-Monel cages).

It is recalled (1) that one of the earlier tests, Run #E-4, was considered an aborted test due to excessive oil leakage and, therefore, has not been included in the group for which maximum likelihood life estimates were obtained. Of the 30 bearings (15 tests) considered for these estimates, fourteen bearings (7 tests) reached their time-up life of 90 hours (231.1 mill. revs.) without failure or surface distress. Testing of sixteen more bearings (8 tests) was terminated without true fatigue failures at lives ranging from 48.8 to 209.4 mill. revs. In five of these latter eight tests, viz #E-16, E-7, E-6, E-10 and E-8, one of the two test bearings in each test smeared or suffered lubrication-related surface damage badly enough so that the tests could not continue at lives ranging from 48.8 to 168.5 mill. revs. In two other tests, #E-3 and E-13, the cages and inner-ring lands wore excessively on one of the two bearings in each test at lives from 134.0 to 209.4 mill. revs. Surface distress in the ball path of one bearing in the one remaining test, #E-9, was attributed to the cage shattering after 169.0 mill. revs., probably from lubricant starvation caused by a vibration-induced loose oil tube when a gear box-bearing failure occurred. The companion bearing in each of these tests was in good condition and, according to the Rules for interpretation of smearing and flaking failures given in the Appendix, was considered to be suspended. Cage wear occurred only with S-Monel cages used in the earlier tests and in no case did excessive wear occur on silver-plated M-1 cages. Hard coke deposits were noted in all test bearings, especially in Runs #E-8, E-10 and E-16 which were the only tests cooled down and restarted over a weekend during the course of testing. It is believed that these deposits may have precipitated smearing occurrences. There was no evidence of silver smeared on the raceways of smeared bearings, so the possibility of bearing failure being precipitated by cage wear is discounted. The three tests, Runs #E-8, E-10 and E-16, are considered as suspended tests, as well as the two tests, Runs #E-3 and E-13, in which cage wear occurred, leaving the failed (smeared) bearings in Runs #E-6 and E-7 as the only legitimate failures for this group.

Inasmuch as surface distress and cage wear in these bearings has occurred without legitimate fatigue failures, it is concluded that the 42,800 rpm and 500°F test condition is on the edge of the safe operating zone for this bearing-lubricant material combination and that the time-up life of 231.1 mill. revs. is below the inherent endurance life capability of the bearing-lubricant combination under these conditions. Therefore, a second group of 30 bearings (15 tests) was tested with the same oil and under the same operating conditions as in the first group except under a thrust load of 459 lbs. for a computed L_{10} = 240 mill. revs. (C/P = 6.2), in the hope that fatigue life would be shortened more than life to lubrication-related failure, and is described next.

CVM M-1 Bearings at 500°F with Turbo Oil 35 Under 459 Lbs. Load

A summary of the test results obtained with this group is given in Enclosure 13. In three tests, (Runs #E-20, E-35, and E-21) five bearings reached their time-up life of 231.1 mill. revs. without failure, while the sixth bearing (from Run #E-21) was found at the time-up point to have suffered a true flaking fatigue failure. Four other bearings (2 tests, Runs #E-20 and E-35) were terminated at lives of 26.8 and 230.8 mill. revs., respectively, when one of the two bearings in each test flaked. The remaining twenty bearings (10 tests) were terminated at lives ranging from 31.6 to 216.0 mill. revs., when one or both bearings in each test smeared or suffered lubrication-related surface damage badly enough so that the tests could not continue. Hard coke deposits were again observed in all the bearings, especially in Run #E-18, which had been cooled down over the weekend shutdown period and then restarted. Since one of the bearings in this test was smeared and no trace of silver was found in its ball path, it is believed that the hard coke deposits promoted this premature failure. Therefore, both bearings in this test were treated as suspended tests.

CVM M-1 Bearings at 500°F with Turbo Oil 35 Under 580 Lbs. Load (One Test)

In order to determine the maximum load carrying capability of the CVM M-1 bearing-Esso Turbo Oil 35 lubricant combination, one additional test was run under the same conditions as the above first two bearing groups, except that the thrust load was further increased to 580 lbs. for a computed L_{10} = 120 mill. revs. After 115.3 mill. revs., one bearing smeared and it was noted that the ball track in the smeared bearing was slightly overriding the groove edge on the inner race, while the companion bearing was in good condition. Results of the test indicate that 580 lbs. is, to all appearances, too high a thrust load to apply to these bearings for proper location of the ball track in the inner raceway groove. A summary of these test results is shown in Enclosure 14.

CVM M-1 Bearings at 595°F with Skylube 600 Under 459 Lbs. Load

Endurance testing of a group of 22 bearings of CVM M-1 steel was completed with the five-ring polyphenyl ether Skylube 600 (PWA 524) as the lubricant at mean temperatures up to 595°F, 459 lbs. thrust load and 42,800 rpm. Results from these 22 bearings tested in the standard N_2 atmosphere (shown in Enclosure 15) indicate that lubrication-related surface distress occurs within several minutes after startup and consequently exception was taken to Rule 2 (given in the Appendix) for conducting endurance tests, viz, unfailed companion bearings were re-run in subsequent tests, in order to conserve available CVM M-1 steel bearings. Twenty of these bearings accumulated lives ranging from .03 to 5.4 mill. revs. In spite of the very short life, 14 bearings were smeared or surface distressed and only 6 bearings were in good condition. In one instance, two bearings (Run #E-23) reached 98.6 mill. revs. However, it was observed the one bearing had glazed and flaked, and its inner race land was worn almost completely away. The companion bearing was in good condition.

CVM M-1 Bearings at 481°F with Skylube 600 Under 365 Lbs. Load

Because of the short lives experienced under 459 lbs. load with Skylube 600 (PWA 524), three test runs were conducted with the same oil and at the same speed but under 365 lbs. thrust load in a N_2 atmosphere. Of the bearings tested, three smeared at lives ranging from .03 to 1.36 mill. revs. The three companion bearings were in good or slightly glazed condition. Summarized results of this group are given in Enclosure 16.

Re-examination of Test Procedure

In view of the short lives obtained in tests conducted with the Skylube 600 (PWA 524) oil, a thorough examination of the rotating parts, machine alignment, and start-up procedures were made in comparison with that used in the long life tests obtained with Esso Turbo Oil 35. No significant difference was observed, and it is concluded that this performance is unavoidable under the test conditions when tests are run with Skylube 600. As a further check on the operation, a test (Run #58) was conducted in which the bearings were lubricated with Kendex Bright Stock 0846 oil (known to have given very satisfactory performance in previous tests). The same start-up procedure and rotating parts were used in this test as used in the tests conducted with Skylube 600. As shown in Enclosure 3, both bearings were in good condition after 90 hours (231.1 mill. revs.) at mean temperatures up to 571°F, 42,800 rpm and under 459 lbs. thrust load. This test further substantiated the fact that the Skylube 600 oil was not giving satisfactory performance but that the test procedure is valid.

CVM M-1 Bearings at 600°F with Skylube 600
Under 459 Lbs. Load (In Air)

Since the standard N_2 inerting of the tester for reduction of oxidative decomposition of the lubricants is not required with Skylube 600, which has inherent high-temperature oxidative stability, and since oxide films formed from an oxidizing atmosphere may improve the glazing resistance of a bearing or boundary lubricating properties of an oil, four additional tests (8 bearings) were conducted with Skylube 600 lubricating the bearings, at 42,800 rpm, 459 lbs. thrust load and mean temperatures up to 600°F, while air replaced the N_2 atmosphere. Enclosure 17 gives the summarized test results. One test, Run #E-47, was conducted for an initial 6.7 hours with static air in the system, except for a small flow of N_2 sealing the load plug clearance; thereafter, the remaining 23.0 hours of this test, as well as all subsequent tests in this group, were conducted with air blanketing both the oil sumps and the test chamber in the same manner in which N_2 blanketing is normally provided. Of the eight bearings tested, two tests, #E-47 and E-48, involving 4 bearings, were terminated at lives of 76.3 and 189.3 mill. revs., respectively. Three of these four bearings were smeared and/or exhibited surface distress; whereas, the fourth bearing was in good condition. In the remaining two tests, #E-45 and E-46, two of the four bearings were smeared at lives of .08 and .05 mill. revs., respectively, while their companion bearings were in good condition.

CVM M-1 Bearings at 598°F with XRM 109F-1
Under 459 Lbs. Load

A group of 10 bearings (5 tests) has been endurance tested to date with Socony XRM 109F-1 oil at 42,800 rpm, mean temperatures up to 598°F and under 459 lbs. thrust load. A summary of the results is given in Enclosure 18. Of the ten bearings tested, six bearings (3 tests, #E-53, E-54 and E-55) were terminated at lives ranging from 2.2 to 17.5 mill. revs., when three bearings either glazed and flaked or smeared, while their companion bearings were in good or superficially pitted condition. Two of the remaining four bearings (2 tests, #E-56 and E-57) were terminated at 8.5 and 2.4 mill. revs., respectively, because they actuated the vibration shutoff. It was found upon inspection that they had undergone lubrication-related surface distress (but were still operable) while their companion bearings were in good condition.

Discussion of Phase II Results

Weibull plots have been prepared for each of the groups endurance tested, as follows:

a. Only legitimate failures were plotted as failures, as determined by the rules given in the Appendix. All other terminated bearings, including those which smeared upon restart and exhibited hard coke deposits were plotted as discontinuances; aborted tests were not plotted.

b. All types of failures, including flaking, lubrication distress and cage induced failures, were plotted as failures in order to determine the overall reliability of each group. Where two bearings failed in the same test, one was treated as a discontinuance, along with the unfailed terminated bearings; aborted tests were not plotted.

Maximum likelihood life estimates, also described in the Appendix, were obtained according to both (a) and (b) above for each test group.

Turbo Oil 35 at 365 lbs. Load

The two Weibull plots for the bearings tested with Esso Turbo Oil 35 at 365 lbs. thrust load are given in Enclosures 19 and 20. As shown on Enclosure 19, the maximum likelihood estimated L_{10} = 480 mill. revs. From Enclosure 20, the maximum likelihood estimated L_{10} = 116.9 mill. revs., which is 24.4% of the AFBMA computed L_{10} life. The life of L_{10} = 480 mill. revs. corresponds to a reduction of the basic dynamic capacity to 80.2% of that computed using AFBMA formulas.

Turbo Oil 35 at 459 lbs. Load

The Weibull plots for the bearing tested with Esso Turbo Oil 35 at 459 lbs. thrust load are given in Enclosures 21 and 22. The corresponding maximum likelihood estimated L_{10} = 58.5 and 47.7 mill. revs., respectively, which yield 24.4 and 19.9% of the AFBMA computed L_{10} = 240 mill. revs. In the former instance, this corresponds to a reduction in the basic dynamic capacity to 62.5% of that computed using AFBMA formulas.

Skylube 600 at 459 lbs. Load

Attempts to perform maximum likelihood life estimates for data obtained at 459 lbs. thrust load, with the bearings lubricated with Monsanto's Skylube 600 (PWA 524) both in N_2 and in an air atmosphere, were unsuccessful due to the wide variation in bearing life within these groups. However, as observed from the Weibull plots in Enclosures 23, 24 and 25, approximately 91% of the bearings tested in a N_2 atmosphere failed at extremely short lives; whereas, only 50% of the bearings tested in air failed at similar short lives.

Skylube 600 at 365 lbs. Load

A Weibull plot of the results obtained with the bearings lubricated with Monsanto's Skylube 600 (PWA 524) at 365 lbs. thrust load in a N_2 atmosphere is given in Enclosure 26. Since the same number of failures were obtained whether considered as in (a) or in (b), described previously, only one Weibull plot is applicable here. The maximum likelihood estimated L_{10} = 0.031 mill. revs., which is only 0.013% of the AFBMA computed L_{10} = 240 mill. revs., indicating that this bearing-lubricant combination had very short life indeed.

Samples of the formulated oil, Skylube 600 (PWA 524), taken from Test Runs #E-23, E-32 and E-33, together with a sample of used OS-124 oil from previous Phase I tests, were given to the Monsanto Company for analysis. Their comments were:

> "The analytical report shows that the major constituent of the deposits is iron with molybdenum as a minor constituent and trace quantities of copper, nickel and chromium. Before the deposits were ashed and examined, they were extracted to remove the base fluid and any soluble materials. Since the analysis was not run quantitatively, we do not know the relative proportion of carbonaceous material to metallic materials. However, the general

consensus of opinion indicates that the metallic present is in about equal proportions to carbonaceous material....

"The conclusions to be drawn from this analysis indicate the deposit to be largely wear debris. It would appear that as the debris is being formed, a sufficient amount of fluid is being degraded at the particular site to become attached to the wear particle, resulting in what is essentially a detergent type action. The degradation product of the fluid attached to the wear particle allows sufficient attraction for the base fluid that it remains suspended."

XRM 109F-1 at 459 Lbs. Load

The Weibull plots of the bearings lubricated with Socony Mobil XRM 109F-1 at 459 lbs. thrust load are given in Enclosure 27, considering only smearing and flaking failures, and in Enclosure 28, considering all failures. Maximum likelihood estimated L_{10} = 3.17 and 2.03 mill. revs., respectively, corresponding, for the first, to 1.3% of the AFBMA computed L_{10} life, which is very low. The low life is due entirely to smearing failures and the explanation of these is given below.

Discussion of Early Smearing Failures

Of the three lubricants run in Phase II endurance tests, the Turbo Oil 35 consistently lubricated a large number of bearings without occurrence of early smearing failures. A large proportion of the bearings run with Skylube 600, however, suffered very early smearing failure, as if stable lubrication conditions could not be established even during the start-up of these tests. Bearings that survived the initial start-up period had quite long life. Many early smearing failures also occurred with the XRM 109F-1 lubricant, although not as soon after start-up as with Skylube 600.

Since neither the XRM 109F-1 nor Skylube 600 contain anti-wear additives, whereas the Turbo Oil 35 is a compounded lubricant, it seems that the present high-speed operating conditions may be at just some critical point where the presence of the proper additives is required to establish stable run-in conditions on the bearing surfaces for reliable long-term smearing-free operation. The possibility of obtaining suitable additives for both of these base-stocks will be explored.

It is conjectured that surface damage (smearing) on the balls and raceways may occur from ball skidding possibly during accelerations of the balls in the tracks at start-up. Gyroscopic slip may also occur, even under constant speed running, if the tangential tractive forces at the ball-race contacts are not great enough to overcome the slip forces generated as the ball spin axes are forced to change direction, while the balls roll around the bearing. A computer analysis of the contact friction required to prevent this gyroscopic slip under the present test conditions* indicates that the bearing thrust loads used in these tests are about three times greater than needed to prevent gyroscopic skidding based on test experience with various size angular-contact ball bearings operating under a variety of loads, speeds, and lubrication conditions. For this reason and in view of the very early occurrence of most smearing failures, start-up accelerations are the prime suspect in causing skidding of balls. Even if a small amount of smearing has occurred in start-up, it depends on the lubrication whether this will increase to cause failure and at what rate. Thus, it is conceivable that some lubricants will produce smearing failures sooner than others and that good enough lubricants will prevent them altogether.

The recent poor results with XRM 109F-1 are contrary to results of previous Phase I tests in which this oil seemed to provide satisfactory lubrication of tool steel bearings at temperatures up to 600°F without early smearing failures at both 20,000 and 40,000 rpm. All previous tests with this oil were run with bearings having rings with cross-groove surface roughness of 6-8 microinches, rms; whereas, the recent Phase II test bearings have an improved surface finish (3-5 microinches,

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*The computer analysis of the 7205 test bearings was furnished by courtesy of Pratt and Whitney Aircraft Division of United Aircraft Corporation.

rms) on the inner-ring groove. It is believed that the improved finish provides better overall freedom from lubrication-related surface distress over long periods of running. It is conceivable, on the other hand, although it has not been shown to date, that ball skidding occurs more readily with the smoother finish under acceleration conditions. A few repeat tests will be run with bearings having the rougher finish to see if the occurrence of early smearing failures is reduced.

Typed:rz

LIST OF REFERENCES

1. Wachendorfer, C. J., "Bearing Lubricant Endurance Characteristics at High Speeds and High Temperatures," Progress Report No. 9, NASA Contract No. NASw-492, January (1965).

2. Morrison, T. W., Tallian, T., Walp, H. O., Baile, G. H., "The Effect of Material Variables on the Fatigue Life of AISI 52100 Steel Ball Bearings," ASLE Transactions, Vol. 5, No. 2, November (1962).

3. Lieblein, J., Zelen, M., "Statistical Investigation of the Fatigue Life of Deep Groove Ball Bearings," Journal of Research, National Bureau of Standards, Vol. 57, No. 5 (1956).

4. Tallian, T., "Weibull Distribution of Rolling Contact Fatigue Life and Deviations Therefrom", ASLE Transactions, Vol. 5, 1, April (1962).

5. McCool, J., Tallian, T., "Estimating Weibull Parameters From Censored Data by Maximum Likelihood" - To be published.

APPENDIX

ANALYSIS OF ENDURANCE TEST RESULTS

Rules for Estimating Life Parameters for Bearings Run Under Extreme Lubrication Conditions

For the purpose of preparing the maximum likelihood life analysis of Phase II endurance test bearings, as described on the subsequent pages of this Appendix, the endurance results are processed according to the following rules:

1. A bearing is considered failed if any of its elements (except, of course, the cage) suffer fatigue flaking.

2. Both bearings in a test assembly is started on test at the same time. In the event both bearings fail, one is considered a failed bearing and the other, an induced failure, and thus is treated as a suspension.

3. Should only one of two bearings fail in a test, the unfailed bearing is considered a suspended test. It will not be run further.

4. If only the cage of a bearing fails (e.g. excessive bore wear, cracked cage pockets), the cage is replaced and the test continued.

5. If cage failure and bearing fatigue failure exist in the same bearing so that it can be assumed that the cage failure has contributed to the premature failure of another element, then the fatigue failure will be considered an induced failure and treated as a suspended test.

6. Surface distress will not be considered a failure if the bearing can be run further. If, however, surface damage is so severe that the bearing cannot be run further, this mode of failure will be treated the same as a fatigue failure.

7. The existence of surface distress along with a fatigue failure in a bearing will be noted but not considered a reason for designating the failure as an induced one. Such failures will be considered legitimate in calculating life because surface distress is a consequence of the test conditions and may be unavoidable.

APPENDIX (Cont.)

It is recognized that the exclusion rules 2, 4 and 5 tend to bias resultant life estimates towards longer life. Still, it is felt that these rules must be used in order that operational malfunctioning of the test be kept from derating the inherent endurance capabilities of the bearing-lubricant combination. In order to evaluate the overall bearing-lubricant reliability under the current state of operational development, however, a second life estimate is conducted for each test group including all failures which otherwise are considered as suspended tests under exclusion Rules 4 and 5. (Failures of the companion bearing in tests where both bearings fail are still treated as suspended tests, according to Rule 2, even when considering overall bearing-lubricant reliability, since companion bearing failures can be so easily induced by initial failure in a bearing pair under high-speed high-temperature operating conditions.)

APPENDIX (Cont.)

Maximum Likelihood Estimation of Fatigue Life Parameters

In evaluating bearing (or bearing element) endurance tests, a problem arises from the fact that failures will occur or the testing of a bearing will be suspended for reasons other than the inherent fatigue failure of the bearing (or element) under test, so that the bearing lives must be estimated in a manner which takes appropriate account of these extraneous failures. In (2), a method originated by Lieblein-Zelen (3) was used in its modified form involving multiple subgroup randomization.* A closer analysis of the Lieblein-Zelen method has recently shown it to be correct and of satisfactory efficiency for uncensored samples (no unfailed test elements) and for samples truncated at a single life value exceeding all failure lives (test group without extraneous failures terminated at a preselected time). The method is not, however, directly applicable to the situation where extraneous failures (of non-test elements) occur at lives not exceeding the longest fatigue life of a test element, and the expedient suggested in (4) to deal with discontinuances is now recognized as questionable.

McCool and Tallian (5) have recently developed a method of maximum likelihood estimation for the parameters of a Weibull distribution which is applicable to any censored sample (involving discontinued tests or extraneous failures) provided only that the times at which censoring occurs are independent of the fatigue life of the failed test elements. As described in (5), this new method consists of the following principal steps:

(a) The likelihood function pertaining to the lives of a censored sample of endurance tested bearings or elements, of which m_1 have failed, is written as

$$\log \mathcal{L} = \sum_{k=1}^{m} \log f_i(L_k) + \sum_{j=m_1+1}^{M} \log[1 - F_i(L_j)] + R \qquad [1]$$

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* The Lieblein-Zelen method as applied to bearing endurance life evaluation is discussed in more detail by Tallian (4).

APPENDIX (Cont.)

where:

$f_1(L)$ is the probability density function of the life distribution of the element,

L_k is the life at failure of the k-th failed element (taken in random order),

$F_1(L)$ is the cumulative distribution function of the life distribution of element,

L_j is the life at which testing of the j-th un-failed element was discontinued, and

R is a term containing only quantities independent of the element life distribution.

It is assumed that the test element has a Weibull life distribution (with unknown scale parameter L_{10} and a dispersion parameter e, but with zero minimum life).

Then, from the definition of a Weibull distribution (4)

$$f_1(L) = \frac{Ke}{L_{10}^{e}} L^{e-1} \exp\left\{-K\left(\frac{L}{L_{10}}\right)^{e}\right\} \qquad [2]$$

$$F_1(L) = 1 - \exp\left\{-K\left(\frac{L}{L_{10}}\right)^{e}\right\} \qquad [3]$$

where

$$K = \log\frac{1}{0.90} = 0.105361$$

APPENDIX (Cont.)

Substitution of Eqs. [2] and [3] into Eq. [1] yields the explicit formula for the likelihood function.

It is shown in (5) that an estimator with many desirable properties, the so-called maximum likelihood estimator can be obtained for the parameters L_{10} and e by finding values of these parameters which maximize the likelihood $\mathcal{L}$ defined by Eq. [1]. This "maximum likelihood" method of estimation is applicable to the situation where competing failure mechanisms operate (i.e., where elements other than the failed elements are also subject to failure) provided only that the lives of elements other than the failed elements are statistically independent of the failed element lives. In case a test is arbitrarily terminated, it is necessary to require that the termination rule be independent of the lives of the test elements, i.e., that it be established without benefit of information regarding the outcome of the test itself. These requirements are usually fulfilled in bearing fatigue tests.

As shown in (5), the determination of the L_{10} and e values maximizing [1] is best accomplished by computing the partial derivatives $\partial \log \mathcal{L} / \partial L_{10}$ and $\partial \log \mathcal{L} / \partial e$ and setting

$$\left.\begin{aligned} \frac{\partial \log \mathcal{L}}{\partial L_{10}} &= 0 \\ \frac{\partial \log \mathcal{L}}{\partial e} &= 0 \end{aligned}\right\} \qquad [4]$$

with suitable verification that the L_{10} and e values satisfying Eq. [4] give indeed a maximum of $\mathcal{L}$.

Eq. [4] is a system of two simultaneous equations in L_{10} and e. It cannot be solved analytically. A computer program was, therefore, written which supplies a solution by the iterative Newton-Raphson method. Using an IBM 1620 computer, a solution for a group of lives can be obtained within a few minutes. Given L_{10} and e, it is then possible to compute L_{50} from the formula

$$L_{50} = \left(\frac{\log 2}{K}\right)^{1/e} L_{10} = (6.57881)^{1/e} L_{10} \qquad [5]$$

APPENDIX (Cont.)

The values of L_{10}, L_{50} and e, with which the computer-estimated Weibull lives in Enclosures 19, 20, 21, 22, 26, 27 and 28 were plotted, were computed in the manner described.

The maximum likelihood method of estimation does not directly yield confidence limits. The one-sigma confidence limits of L_{10} for a test group of 30 bearings were obtained by a Monte Carlo method described in (5) which operates essentially as follows: Sets of random numbers having a Weibull distribution with zero minimum life, a known value of L_{10}, and several known values of e are numerically generated. These samples of Weibull distributed numbers are subjected to censoring by a method simulating the censoring occurring in the life tests considered. Each censored sample of numbers is then subjected to the maximum likelihood estimation method described above, giving numerous estimates of the parameter L_{10}.

The standard deviation $\sigma_{L_{10}}$ of this group of L_{10} estimates is computed and expressed as a fraction $\sigma_{L_{10}}/L_{10}$ of the population value of L_{10} and as a function of the population Weibull slope e. In this manner, the graph shown in Enclosure 29 was plotted. Given the maximum likelihood estimates for L_{10} and Weibull slope e for a bearing life test group, it is now possible to read from Enclosure 29 the value of $\sigma_{L_{10}}/L_{10}$ applicable to the estimated value of e. For any test group containing 30 bearings, $\sigma_{L_{10}}/L_{10}$ is read from Enclosure 29, multiplied by the L_{10} estimate for that group, and added and subtracted from L_{10} to form upper and lower one-sigma confidence limits. For groups of size other than 30, a correction proportional to the square root of the group size is applied to $\sigma_{L_{10}}$. This method of obtaining confidence limits is admittedly approximate since the censoring conditions used in the Monte Carlo study are not exactly the same as those encountered in the life tests. It has been shown, however (5), that the effect of minor differences in truncation on the confidence band for L_{10} is small as long as no discontinuance occurs prior to L_{10}.

ENCLOSURE 1

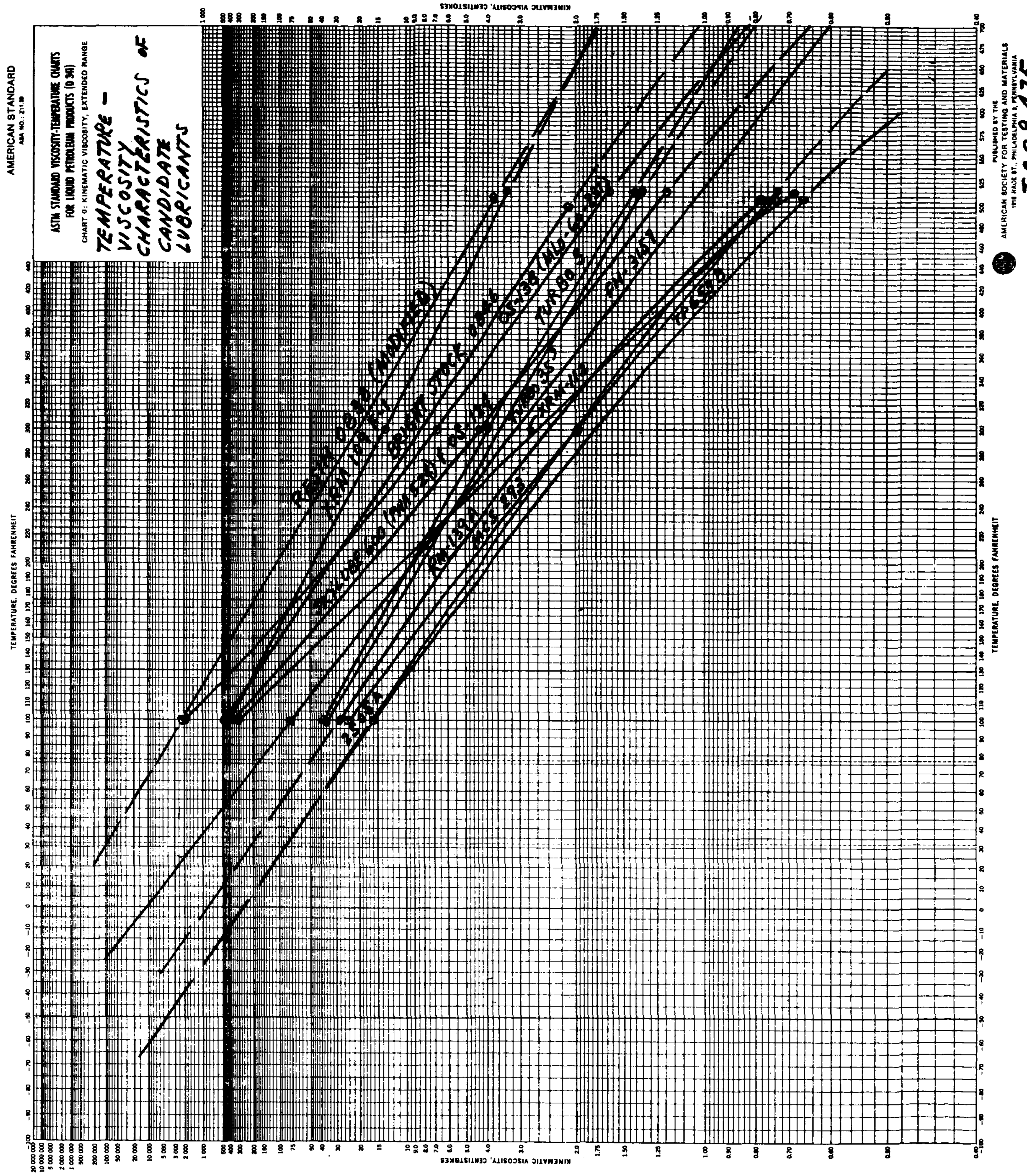
SKF 7205 ANGULAR CONTACT TEST BEARING DIMENSIONS BEFORE TEST

Bearing No.	Surface Finish (10^{-6} in., rms) I.R.	Surface Finish (10^{-6} in., rms) O.R.	Average Outside Diameter (Microns)	Average Bore Diameter (Microns)	Contact Angle (Degrees)	Average Radial Looseness (Microns)	Average Radial Cage Play (Inches)	Taper (Microns) O.R.	Taper (Microns) I.R.	Out of Roundness (Microns) O.R.	Out of Roundness (Microns) I.R.
201	*	*	51.998	24.996	20.8	50	.0068	1.5	1.5	5.0	2.0
202	*	*	51.995	24.997	20.4	45	.0067	3.0	0.5	2.0	2.0
203	*	*	51.997	24.997	20.4	48	.0065	0.5	0.0	4.0	2.0
204	*	*	51.997	24.997	18.8	48	.0070	1.0	1.0	3.0	1.0
205	*	*	52.000	24.996	19.9	48	.0065	1.0	1.0	2.0	1.0
206	*	*	51.995	24.999	19.5	47	.0065	1.5	1.0	2.0	1.0
207	*	*	51.996	24.995	19.9	48	.0070	1.0	1.0	3.0	1.0
208	*	*	51.999	24.996	19.0	49	.0070	2.5	0.0	3.0	1.0
209	*	*	51.995	24.996	18.3	35	.0065	2.0	1.0	2.0	2.0
210	*	*	51.999	24.998	21.8	48	.0065	0.0	0.5	2.0	2.0
211	*	*	51.997	24.996	20.4	50	.0068	1.0	0.0	2.0	1.0
212	*	*	51.995	24.997	20.8	51	.0068	3.5	0.0	2.0	1.0
213	*	*	51.996	24.997	21.2	51	.0070	1.5	1.0	3.0	2.0
214	*	*	51.996	24.996	20.4	51	.0065	5.0	1.0	2.0	1.0
218	*	*	51.996	24.997	21.7	52	.0060	1.5	0.0	3.0	1.0
219	*	*	51.998	24.996	19.0	48	.0065	3.0	0.0	2.0	2.0
220	*	*	51.995	24.998	19.5	45	.0065	1.0	0.0	3.0	1.0
221	*	*	51.997	24.996	19.5	48	.0065	2.0	1.0	3.0	1.0
223	*	*	51.996	24.997	20.8	52	.0068	3.0	0.5	3.0	2.0
226	*	*	51.998	24.998	20.8	42	.0065	2.5	0.0	3.0	1.0
227	*	*	51.999	24.999	22.1	52	.0062	1.0	0.0	2.0	2.0
228	*	*	51.996	24.999	21.3	48	.0058	2.0	1.5	5.0	2.0
229	*	*	51.998	24.997	21.3	50	.0068	1.5	0.5	3.0	2.0
230	*	*	51.995	24.997	21.3	50	.0068	4.0	1.0	2.0	1.0
231	*	*	51.999	24.997	20.4	42	.0060	3.5	0.0	3.0	2.0
233	*	*	51.994	24.998	20.8	47	.0068	2.0	0.0	2.0	2.0
234	*	*	51.996	24.999	20.8	49	.0063	1.0	1.0	3.0	1.0
235	*	*	51.996	25.000	20.4	47	.006	1.5	0.5	3.0	2.0
236	*	*	52.000	24.997	21.3	50	.005	0.5	5.0	3.0	3.0
237	*	*	51.997	24.997	20.4	48	.0069	2.5	0.5	3.0	2.0
238	*	*	51.995	24.995	20.8	49	.0060	0.5	0.5	3.0	2.0
239	*	*	51.997	24.997	20.8	48	.0068	2.5	0.0	3.0	1.0
242	*	*	51.996	24.997	20.8	49	.0052	2.5	0.0	3.0	2.0
243	*	*	51.996	24.996	21.3	51	.0065	0.5	1.0	2.0	1.0
244	*	*	51.995	24.997	20.8	49	.0063	2.0	0.5	2.0	2.0
245	*	*	51.997	24.997	19.9	49	.0060	2.0	1.0	2.0	1.0
246	*	*	51.996	24.998	20.4	44	.0070	2.0	0.0	2.0	1.0
247	*	*	51.998	24.998	20.4	48	.0068	2.0	3.0	2.0	1.0
248	*	*	51.999	24.997	21.3	47	.0060	2.0	0.0	2.0	1.0
249	*	*	51.997	24.996	20.4	46	.0060	2.0	1.0	2.0	1.0
251	*	*	51.997	24.998	20.8	48	.0066	1.5	1.0	3.0	2.0
252	*	*	51.999	24.998	20.4	47	.0056	0.5	1.0	3.0	1.0
253	*	*	51.994	24.997	20.4	48	.0079	1.0	1.0	2.0	1.0
254	*	*	51.995	24.998	20.8	47	.0065	2.0	1.0	3.0	1.0
255	*	*	51.998	24.997	20.4	47	.0067	3.0	1.0	2.0	1.0
257	*	*	51.997	24.999	20.4	53	.0052	0.0	0.0	2.0	2.0
258	*	*	51.997	24.998	19.9	48	.0060	1.5	1.0	2.0	1.0
259	*	*	51.995	24.998	19.9	44	.0069	3.5	1.0	3.0	1.0
260	*	*	51.999	24.999	19.0	46	.0069	1.0	0.0	4.0	1.0
261	*	*	51.996	24.995	18.1	47	.0058	0.5	1.0	2.0	1.0
262	*	*	51.995	24.997	20.4	45	.0067	1.5	0.0	4.0	1.0
263	*	*	51.996	24.996	20.8	48	.0058	1.0	1.5	2.0	2.0
264	*	*	51.997	24.998	19.5	47	.0065	1.0	1.0	2.0	1.0
268	*	*	51.994	24.996	20.4	48	.0075	1.0	1.0	2.0	1.0
269	*	*	52.001	24.997	21.3	50	.0075	2.5	0.0	3.0	1.0
270	*	*	51.998	24.997	20.8	46	.0094	0.5	0.0	2.0	3.0
284	*	*	51.996	24.996	19.7	42	.0058	0.0	1.0	2.0	1.0
285	*	*	51.997	24.995	20.7	47	.0052	1.0	1.0	2.0	1.0
301	*	*	51.996	24.996	19.5	45	.0095	2.0	0.0	2.0	1.0
302	*	*	51.997	24.998	20.8	47	.0070	1.0	0.0	2.0	1.0
303	*	*	51.999	24.997	20.4	48	.0092	1.0	0.0	3.0	1.0
304	*	*	51.995	24.997	19.9	53	.0092	0.5	2.5	3.0	2.0
305	*	*	51.999	24.997	20.4	47	.0060	3.5	1.0	3.0	1.0
306	*	*	51.999	24.998	21.3	43	.0073	1.0	3.0	2.0	1.0
307	*	*	51.998	24.997	21.3	51	.0070	2.0	1.0	2.0	1.0
308	*	*	51.999	24.997	21.8	48	.0077	1.0	1.0	2.0	1.0
309	*	*	52.000	24.997	20.8	47	.0082	1.5	1.0	3.0	1.0
310	*	*	51.998	24.997	19.9	49	.0084	2.5	1.0	3.0	1.0
311	*	*	51.993	24.996	20.8	49	.007	0.0	1.0	3.0	1.0
313	*	*	51.997	24.996	19.9	48	.0069	3.0	0.0	3.0	1.0
314	3.4	6.4	51.999	24.998	20.4	48	.0063	0.5	0.5	3.0	2.0
315	3.5	6.1	51.997	24.993	20.4	50	.0065	1.5	3.0	3.0	3.0
316	4.2	6.3	51.996	24.992	20.8	50	.0076	1.5	1.0	4.0	2.0
317	3.7	6.3	52.000	24.997	20.4	48	.0075	2.0	0.0	2.0	1.0
318	3.7	6.7	51.997	24.996	19.9	48	.0070	2.0	0.5	2.0	2.0
319	3.9	5.3	51.996	24.997	19.9	50	.0085	2.5	1.0	2.0	1.0
320	3.8	6.4	51.998	24.997	20.8	49	.0067	2.5	2.0	3.0	1.0
321	3.9	6.1	51.999	24.998	21.3	48	.0050	0.5	0.0	3.0	1.0
323	3.4	4.7	51.999	24.996	20.4	50	.0095	0.5	1.0	2.0	1.0
324	3.5	5.8	51.995	24.996	21.3	44	.0080	1.0	0.5	2.0	2.0
325	3.2	6.1	51.998	24.997	20.4	49	.0069	1.5	0.5	4.0	2.0
326	3.4	4.6	51.998	24.995	20.8	51	.0069	0.0	1.0	3.0	1.0
327	3.5	5.8	51.996	24.996	20.4	48	.0074	1.0	0.5	2.0	2.0
328	3.4	6.7	51.999	24.996	19.5	49	.0073	1.5	1.0	3.0	1.0
332	3.5	6.0	51.996	24.998	19.9	46	.0077	4.0	0.0	2.0	1.0
333	3.5	6.5	51.996	24.999	20.8	48	.0060	1.0	2.0	2.0	1.0
334	3.5	6.7	51.998	24.997	20.4	45	.0078	0.5	1.0	3.0	1.0
335	3.7	7.0	51.997	24.998	18.0	48	.0079	0.0	0.5	2.0	2.0
336	3.5	6.4	51.996	24.996	19.9	46	.0073	2.0	1.0	2.0	2.0
337	3.3	6.9	51.996	24.996	20.8	47	.0069	1.5	0.0	3.0	1.0
338	3.7	7.6	51.998	24.996	21.3	47	.009	2.0	0.0	2.0	1.0
339	3.2	7.1	51.994	24.996	20.4	43	.0085	2.0	1.0	2.0	1.0
340	3.5	6.1	51.996	24.997	21.7	52	.0078	1.0	1.0	3.0	1.0
341	3.2	5.8	51.998	24.996	20.8	50	.0075	1.5	0.0	3.0	1.0
342	3.6	6.9	51.995	24.998	19.9	53	.0074	2.0	1.0	2.0	1.0
343	3.5	7.6	51.999	24.996	21.7	48	.0073	4.5	1.0	3.0	1.0
344	3.5	6.3	51.998	24.998	21.3	41	.0083	1.5	1.0	2.0	1.0
346	4.1	5.9	52.000	24.997	20.4	50	.0081	1.0	1.0	2.0	1.0
347	3.3	6.6	51.996	24.998	20.8	50	.0075	2.5	0.5	2.0	2.0
348	3.5	6.1	51.996	24.996	19.9	47	.0073	1.5	0.0	3.0	1.0
350	3.3	6.9	51.994	24.997	21.7	47	.0069	1.0	0.5	2.0	2.0
351	3.5	7.1	51.996	24.997	20.4	48	.0078	0.5	0.5	3.0	2.0
352	3.9	7.3	51.998	24.999	19.9	44	.0081	0.5	0.0	3.0	1.0
353	3.5	7.0	51.998	24.997	21.3	50	.0081** .0064	0.0	0.5	2.0	2.0
354	3.3	6.3	51.999	24.998	20.4	50	.0084** .0083	1.0	0.0	3.0	1.0
355	3.1	5.9	51.994	24.996	21.7	46	.0095	1.0	1.0	2.0	1.0
356	3.1	6.3	51.997	24.997	20.4	41	.0082	0.0	0.0	2.0	1.0
357	3.6	5.8	51.997	24.996	21.7	46	.0094	1.5	1.0	4.0	1.0
358	3.8	8.0	51.996	24.996	19.9	51	.0083	1.0	1.0	3.0	1.0
359	3.5	6.3	51.998	24.995	21.3	43	.0080	2.0	1.0	2.0	1.0
360	4.1	6.4	51.999	24.998	21.7	47	.0079	2.5	0.0	3.0	1.0
361	3.5	5.9	51.997	24.996	21.3	49	.0076	1.0	0.0	2.0	3.0
362	3.4	6.8	51.999	24.997	19.5	47	.0069	1.5	0.0	2.0	1.0
363	3.3	7.1	51.995	24.996	20.4	41	.0078	0.5	0.0	2.0	1.0
368	3.4	6.9	51.995	24.998	21.7	46	.0090	1.0	0.0	2.0	1.0
369	3.4	6.2	51.995	24.998	19.9	47	.0090	0.5	1.0	3.0	2.0

* Surface finish measurements were not obtained for this bearing.

** The radial cage play for this bearing is given first for the initial cage and then its replacement.

ENCLOSURE 2


AMERICAN STANDARD
ASTM STANDARD VISCOSITY-TEMPERATURE CHARTS FOR LIQUID PETROLEUM PRODUCTS (D 341)
CHART G: KINEMATIC VISCOSITY, EXTENDED RANGE
TEMPERATURE — VISCOSITY CHARACTERISTICS OF CANDIDATE LUBRICANTS
KINEMATIC VISCOSITY, CENTISTOKES
TEMPERATURE, DEGREES FAHRENHEIT
PUBLISHED BY THE AMERICAN SOCIETY FOR TESTING AND MATERIALS
T289-475

ENCLOSURE 3

SUMMARIZED RESULTS OF PHASE I TESTING OF 7205 CVM M-1 STEEL BEARINGS (#455760)

Speed = 42,800 rpm

Run No.	Test Bearing (b) No.	Test Bearing (b) Location	Lubricant	Test Duration Hours	Test Duration 10^6 Revs.	Thrust Load (lbs.)	Mean Temperatures, °F Bearing	Mean Temperatures, °F Housing	Mean Temperatures, °F Oil in Sump	Oil Consumed (ml)	Oil After Test Visc. at 100°F (cs)	Oil After Test Acid No.	Oil After Test Solids (mg/100ml)	(a) Bearing Condition After Test Cage Bore Wear	(a) Bearing Condition After Test (Mils)	(a) Bearing Condition After Test Raceways and Balls
56	223	Drive	Monsanto MCS 293	22.8	58.5	365	516	453	445	465	24.7	.06	67.0	Not Appreciable	<0.1	I.R. & O.R. - Glazed and flaked Balls - Flaked
	245	Load		22.8	58.5		500	453	435					Not Appreciable	<0.1	I.R. & O.R. - Good Balls - OK
57	285	Drive	Sinclair Turbo S	89.5	230.0	365	550	486	460	1975	67.9	.55	105.0	Very Slight	0.8	I.R. & O.R. - Slightly Glazed Balls - OK
	284	Load		89.5	230.0		531	486	395					Cage Shattered	-	I.R. & O.R. - Smeared Balls - Shattered
58	315	Drive	Kendex Bright Stock 0846	90.0	231.1	459	571	495	581	3390	423.2	.08	40.0	Not Appreciable	<0.1	I.R. & O.R. - Good Balls - OK
	314	Load		90.0	231.1		493	495	516					Not Appreciable	<0.1	I.R. & O.R. - Good Balls - OK
59	326	Drive	Monsanto OS-138 (ML)-60-231)	19.6	50.3	365	598	429	578	825	2293.0	.06	152.0	Slight	1.0	I.R. - Slightly Glazed O.R. - Good Balls - OK
	325	Load		19.6	50.3		583	429	525					Excessive	9.2	I.R. - Glazed & Fragment Dented (Lands grooved) O.R. - Glazed Balls - OK

Unused Oil Analysis

	Visc. at 100°F, cs	Acid No.	Solids (mg/100ml)
Monsanto MCS 293	24.8	.06	18.0
Sinclair Turbo S	38.8	.22	1.5
Kendex Bright Stock 0846	446.9	.10	4.4
Monsanto OS-138 (MLO-60-231)	1802.9	.06	3.5

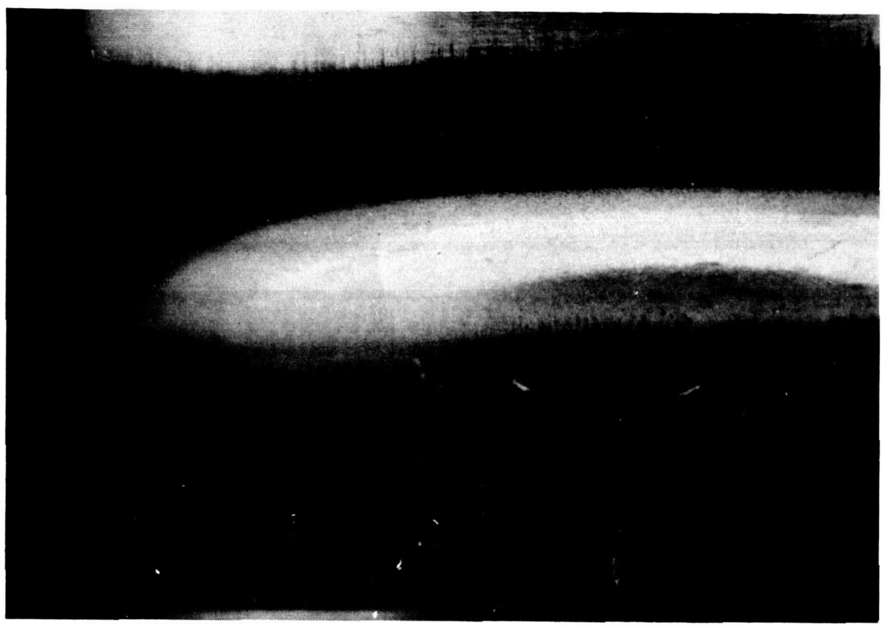
(a) A bearing is considered to be in good condition if after testing the finishing marks produced in manufacturing of the bearing are still evident in the ball path. A slightly glazed bearing is one in which these finishing marks are not as outstanding or are partially removed.

(b) The inner race grooves of these bearings were honed; whereas, their outer race grooves were ground and polished.

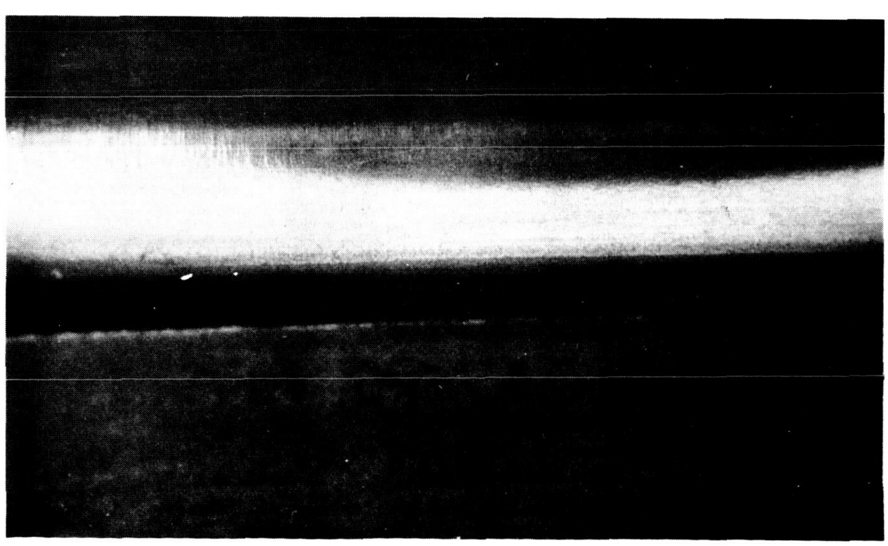
ENCLOSURE 4

UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 58.5 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 500°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING MONSANTO MCS 293 OIL IN A N_2 BLANKET

(Bearing No. 245 On Load End From Run No. 56)



INNER RACEWAY T289-461

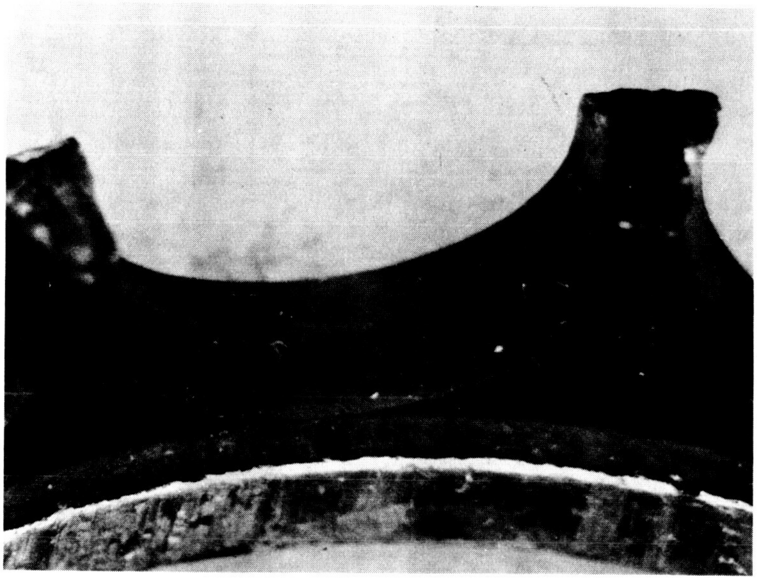


OUTER RACEWAY T289-453

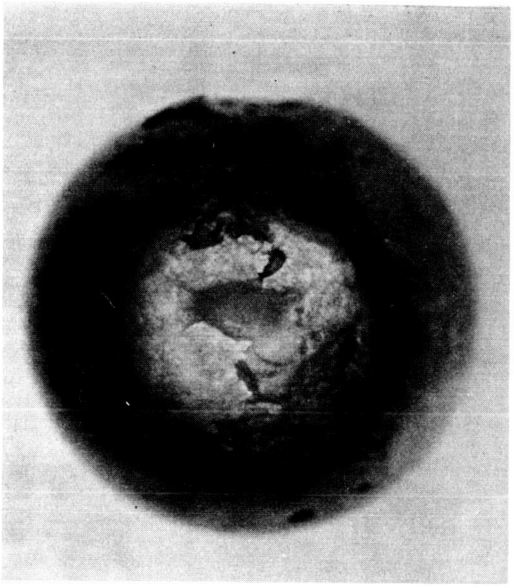
ENCLOSURE 5

FAILED M-1 TOOL STEEL BEARING AFTER RUNNING 58.5 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 516°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING MONSANTO MCS 293 OIL IN A N_2 BLANKET

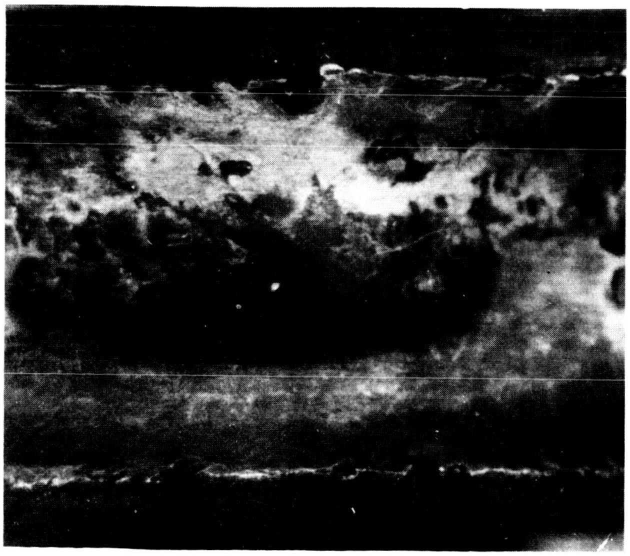
(Bearing No. 223 On Drive End From Run No. 56)



CAGE T289-468



BALL T289-473



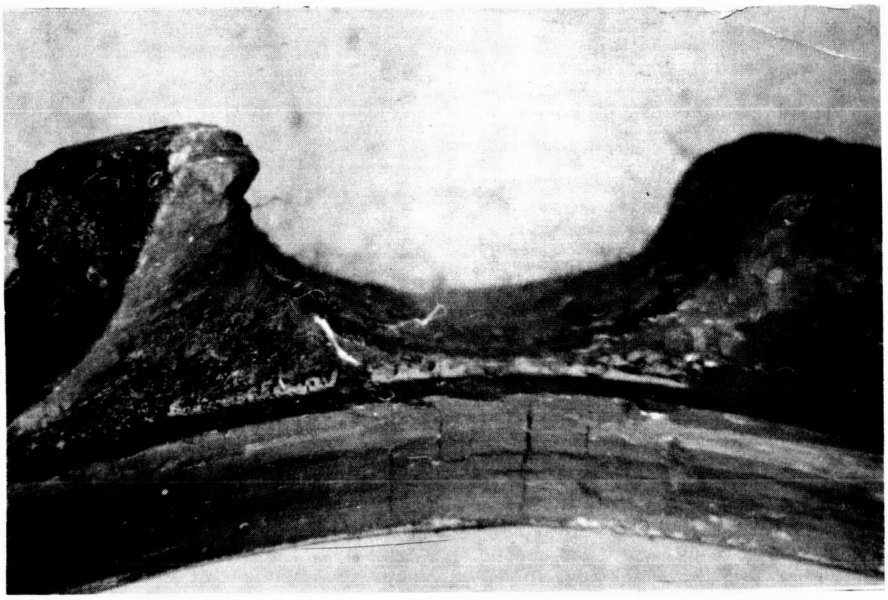
INNER RACEWAY T289-460

OUTER RACEWAY T289-452

ENCLOSURE 6

FAILED M-1 TOOL STEEL BEARING AFTER RUNNING 230 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 531°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SINCLAIR TURBO S OIL IN A N_2 BLANKET

(Bearing No. 284 On Load End From Run No. 57)



CAGE T289-471

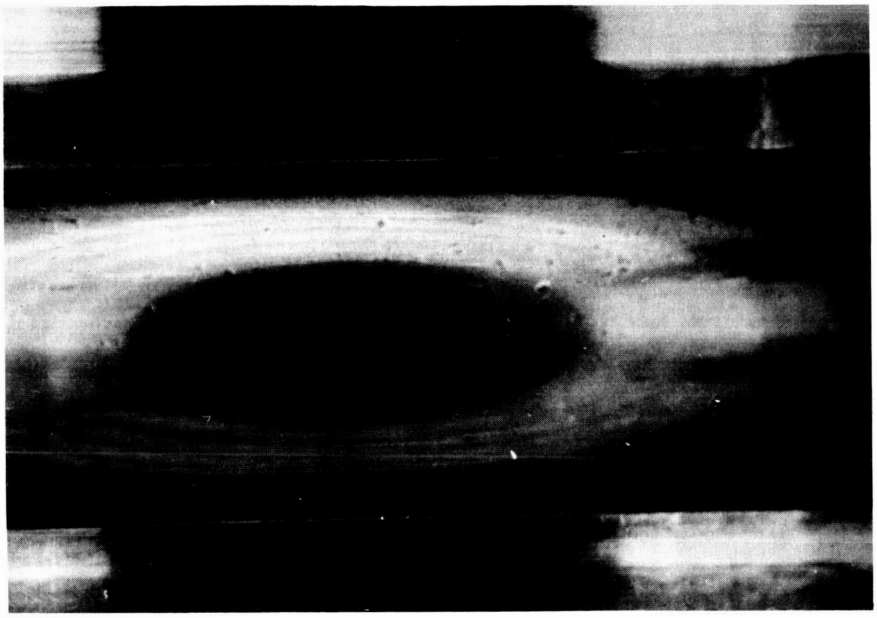
INNER RACEWAY T289-464

OUTER RACEWAY T289-456

ENCLOSURE 7

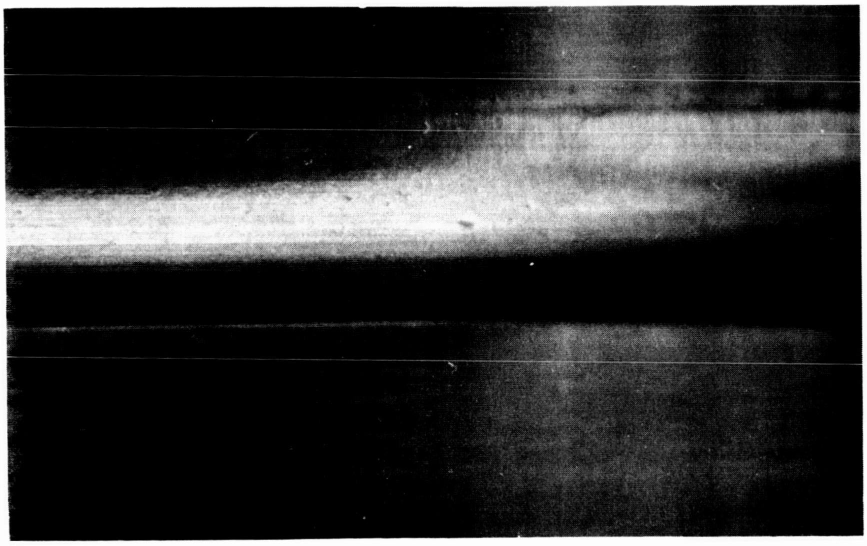
UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 230 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 550°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING SINCLAIR TURBO S OIL IN A N_2 BLANKET

(Bearing No. 285 on Drive End From Run No. 57)



T289-465

INNER RACEWAY



T289-457

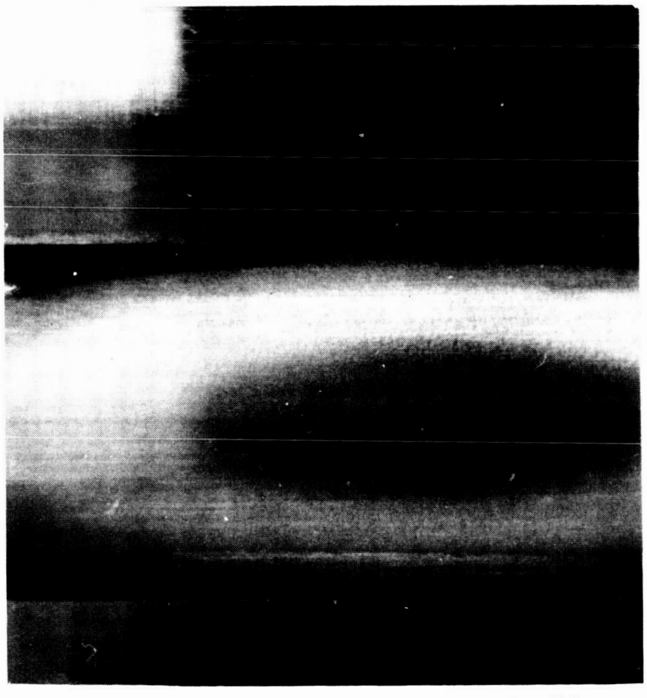
OUTER RACEWAY

ENCLOSURE 8

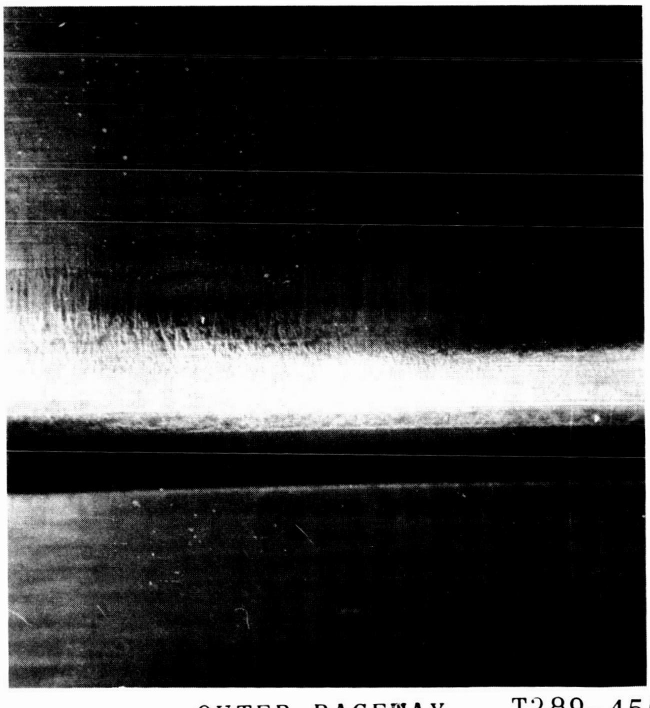
UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 231.1 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 493°F AND UNDER 459 LBS. THRUST LOAD WITH CIRCULATING KENDEX BRIGHT STOCK 0846 OIL IN A N_2 BLANKET

(Bearing No. 314 On Load End From Run No. 58)

CAGE T289-470



INNER RACEWAY T289-463

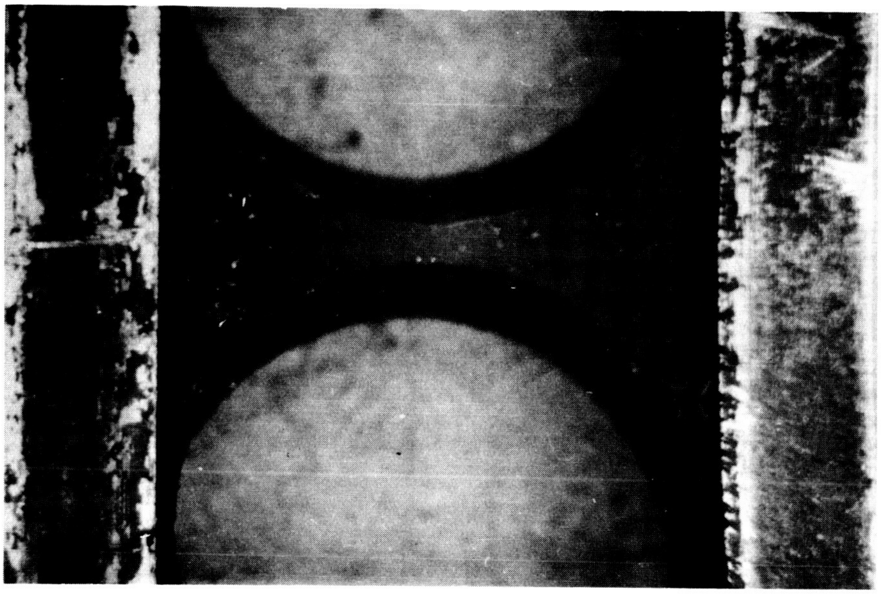


OUTER RACEWAY T289-455

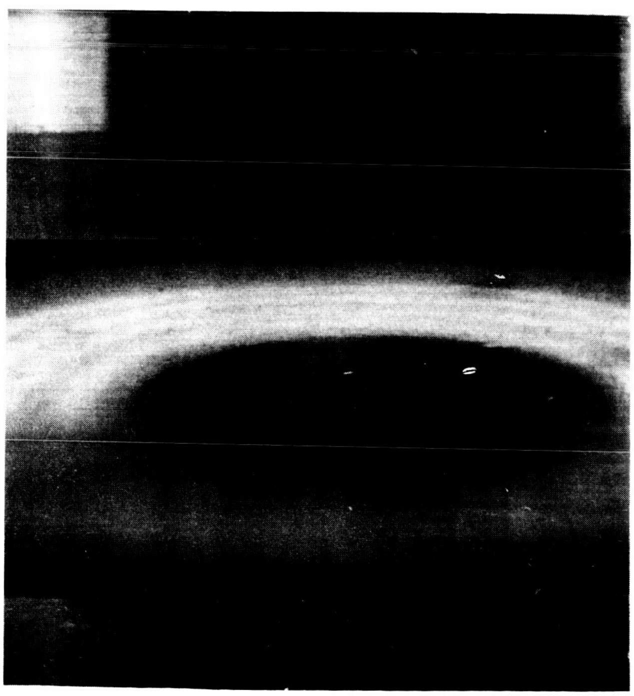
ENCLOSURE 9

UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 231.1 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 571°F AND UNDER 459 LBS. THRUST LOAD WITH CIRCULATING KENDEX BRIGHT STOCK 0846 OIL IN A N_2 BLANKET

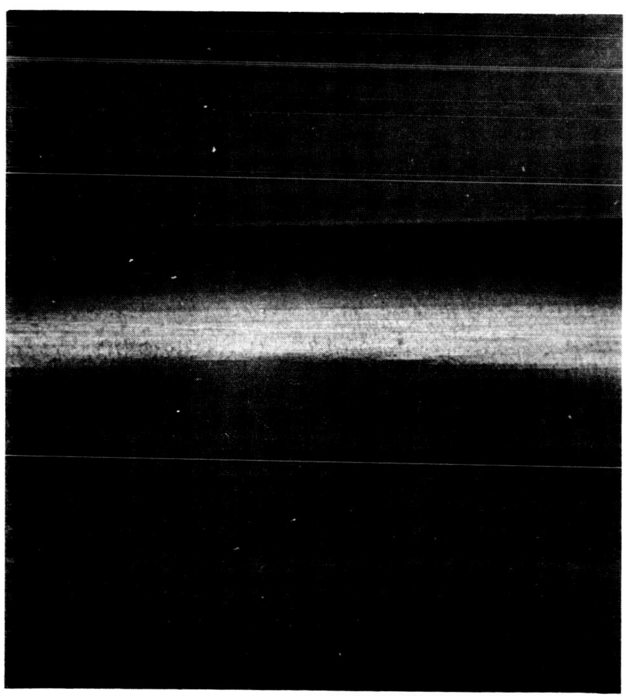
(Bearing No. 315 On Drive End From Run No. 58)



CAGE T289-469



INNER RACEWAY T289-462

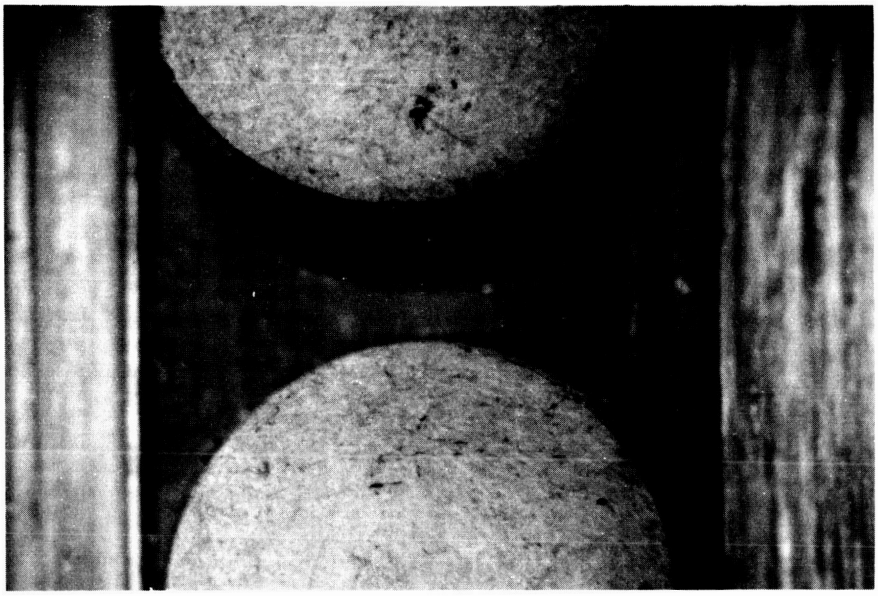


OUTER RACEWAY T289-454

ENCLOSURE 10

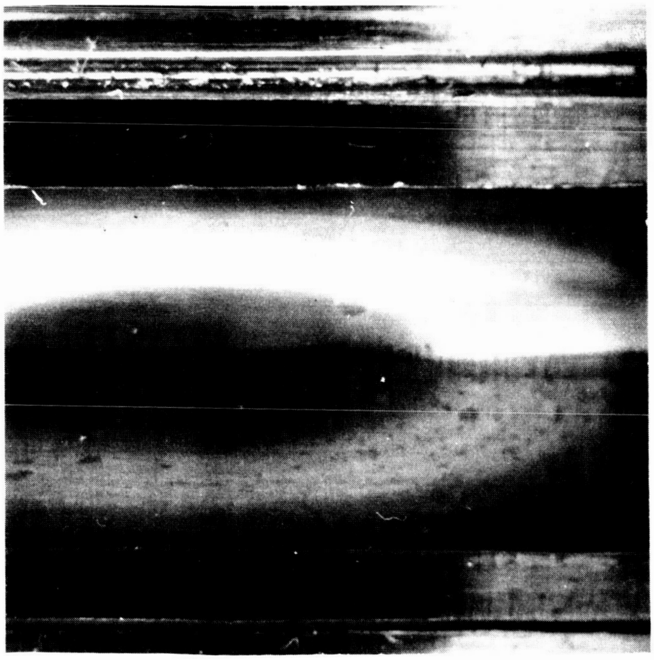
UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 50.3 x 10^6 REVOLUTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 583°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING MONSANTO OS-138 OIL IN A N_2 BLANKET

(Bearing No. 325 On Load End From Run No. 59)



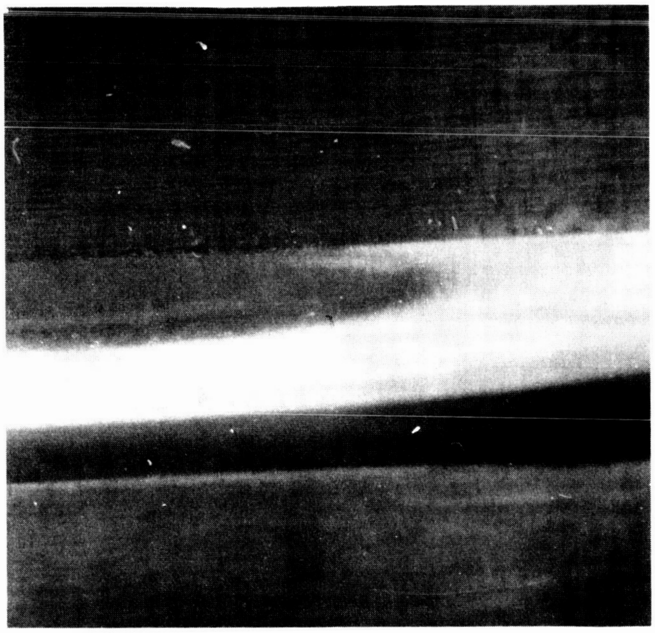
T289-474

CAGE



T289-466

INNER RACEWAY



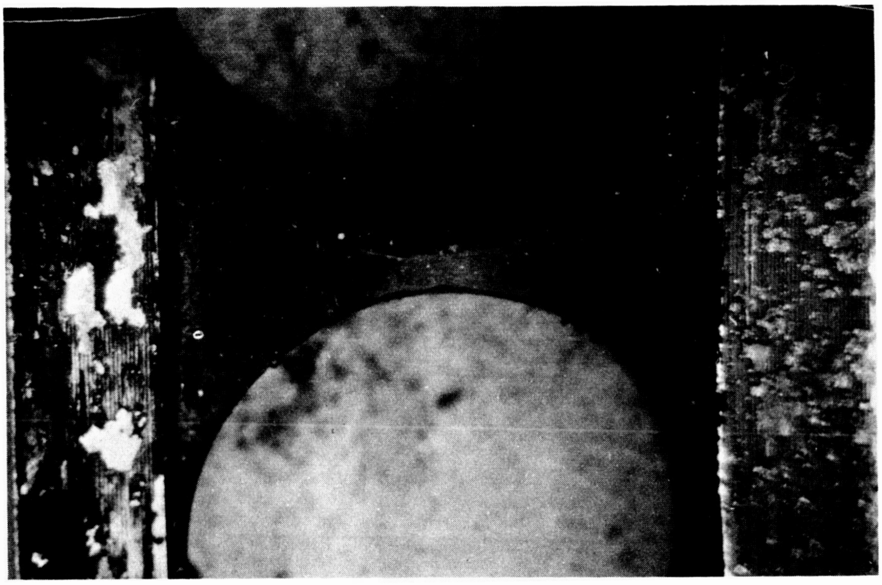
T289-458

OUTER RACEWAY

ENCLOSURE 11

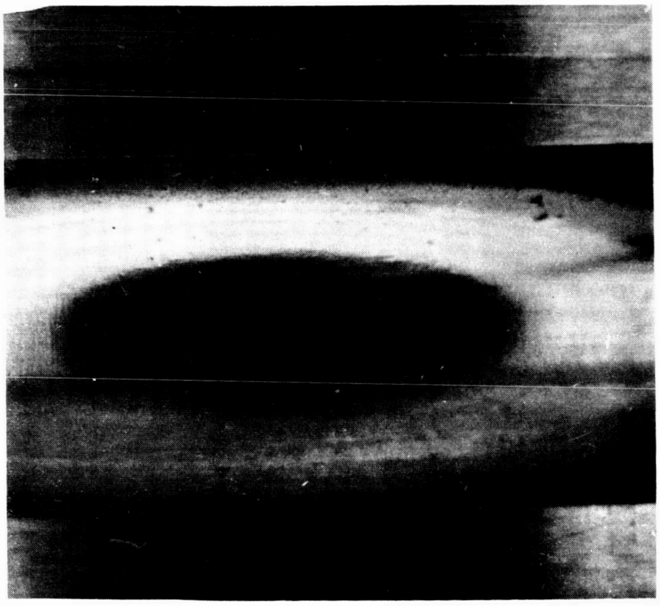
UNFAILED M-1 TOOL STEEL BEARING AFTER RUNNING 50.3 x 10^6 REVOULTIONS AT 42,800 RPM, A MEAN TEMPERATURE OF 598°F AND UNDER 365 LBS. THRUST LOAD WITH CIRCULATING MONSANTO OS-138 OIL IN A N_2 BLANKET

(Bearing No. 326 On Drive End From Run No. 59)

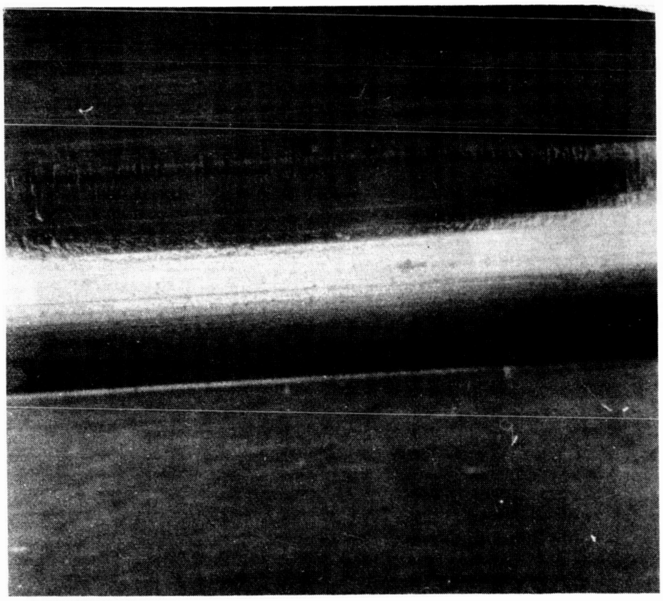


T289-472

CAGE



INNER RACEWAY T289-467



OUTER RACEWAY T289-459

ENCLOSURE 12

ENDURANCE OF CVM M-1 STEEL 7205 BEARINGS (#455760)

Thrust Load = 365 Lbs. Speed = 42,800 rpm Lubricant = Esso Turbo Oil 35

Test Run No.	Bearing No.	Cage Material (1)		Cage Bore Wear, Mils	Avg. Temp. °F	Lubrication Distress Elements(s)	Part(s) Failed	Life 10^6 Revs.
(4) E-4	208(2)	S-Monel	(Rc 33)	43.0	473	I.R., O.R., Glazed	None	7.7
	207	S-Monel	(Rc 33)	0.5	490	None	None	7.7
(5) E-16	242	M-1	(Rc 55)Stl.	<0.1	505	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	48.8
	239	M-1	(Rc 55)Stl.	<0.1	505	None	None	48.8
E-7	221	M-1	(Rc 55)Stl.	<0.1	490	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	101.2
	220	M-1	(Rc 55)Stl.	<0.1	510	None	None	101.2
E-6	214	M-1	(Rc 55)Stl.	<0.1	510	None	None	108.1
	213	M-1	(Rc 55)Stl.	<0.1	485	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	108.1
(5) E-10	228	M-1	(Rc 55)Stl.	<0.1	500	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	122.0
	231	M-1	(Rc 55)Stl.	<0.1	445	None	None	122.0
E-13	234	S-Monel	(Rc 33)	<0.1	509	None	None	134.0
	233(2)	S-Monel	(Rc 33)	40.0	480	I.R. Fragment Dented O.R. Glazed	None	134.0
E-8	219	M-1	(Rc 55)Stl.	<0.1	499	None	None	168.5
	218	M-1	(Rc 55)Stl.	0.5	505	I.R., O.R. - Superfically Pitted	None	168.5
(6) E-9	212	M-1	(Rc 55)Stl.	<0.1	510	None	None	169.0
	211(2)	M-1	(Rc 55)Stl.	- (3)	505	I.R., O.R. - Glazed & Fragment Dented Balls - Flaked & Fragment Dented	I.R., O.R., Balls	169.0
E-3	206(2)	S-Monel	(Rc 33)	21.5	475	I.R., O.R., Slightly Glazed	None	209.4
	205	S-Monel	(Rc 33)	0.2	496	None	None	209.4
E-1	202	S-Monel	(Rc 33)	0.2	485	None	None	231.1
	201	S-Monel	(Rc 33)	<0.1	500	None	None	231.1
E-2	204	S-Monel	(Rc 33)	0.2	500	None	None	231.1
	203	S-Monel	(Rc 33)	<0.1	505	None	None	231.1
E-5	210	S-Monel	(Rc 33)	<0.1	492	None	None	231.1
	209	S-Monel	(Rc 33)	<0.1	515	None	None	231.1
E-11	227	M-1	(Rc 55)Stl.	<0.1	456	None	None	231.1
	226	M-1	(Rc 55)Stl.	0.4	500	None	None	231.1
E-12	230	M-1	(Rc 55)Stl.	<0.1	500	None	None	231.1
	229	M-1	(Rc 55)Stl.	<0.1	470	None	None	231.1
E-14	236	M-1	(Rc 55)Stl.	0.8	460	None	None	231.1
	235	M-1	(Rc 55)Stl.	<0.1	515	None	None	231.1
E-15	238	M-1	(Rc 55)Stl.	0.8	510	None	None	231.1
	237	M-1	(Rc 55)Stl.	<0.1	495	None	None	231.1

(1) The M-1 (Rc 55) steel cages were silver plated on their bores as shown in Enclosure 16 of (1).

(2) The inner race cage land riding surfaces of this bearing was worn excessively.

(3) The cage bore wear for this bearing could not be determined since the cage had shattered.

(4) This test is considered an aborted test because of excessive oil leakage from the sight glass for Bearing No. 208.

(5) Both bearings in this test were considered suspended tests because it was found that excessive coking had formed on the failed bearing during the normal weekend shutdown which contributed to its failure upon restart.

(6) Both bearings in this test are considered suspended tests since failure of the balls in Bearing No. 211 is attributed to shattering of the cage.

ENCLOSURE 13

ENDURANCE OF CVM M-1 STEEL 7205 BEARINGS (#455760)

Thrust Load = 459 lbs. **Speed = 42,800 rpm** **Lubricant = Esso Turbo Oil 35**

Test Run No.	Bearing No.	Cage Material (1)	Cage Bore Wear, Mils	Avg. Temp. °F	Lubrication Distress Element(s)	Part(s) Failed	Life 10^6 Revs.
E-35	319	M-1 (Rc 55) Stl.	1.4	506	None	None	26.5
	318	M-1 (Rc 55) Stl.	0.9	504	O.R. Slightly Glazed I.R. Flaked	I.R.	26.5
E-37	328	M-1 (Rc 55) Stl.	<0.1	491	None	None	31.6
	327	M-1 (Rc 55) Stl.	<0.1	488	I.R. Glazed & Superficially Pitted	None	31.6
(4) E-38	335	M-1 (Rc 55) Stl.	<0.1	550	I.R. - Glazed & Flaked O.R. - Slightly Glazed	I.R.	46.7
	334	M-1 (Rc 55) Stl.	<0.1	470	I.R. - Glazed & Flaked O.R. - Glazed Ball - 7 Flaked	I.R., Balls	46.7
E-36	317	M-1 (Rc 55) Stl.	0.7	529	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	49.6
	316	M-1 (Rc 55) Stl.	<0.1	495	I.R., O.R., Slightly Glazed	None	49.6
E-40	341	M-1 (Rc 55) Stl.	<0.1	550	I.R., O.R., Slightly Glazed	None	54.2
	340(2) (3)	M-1 (Rc 55) Stl.	19.8	540	I.R. - Glazed & Flaked O.R. - Glazed	I.R.	54.2
E-43	343	M-1 (Rc 55) Stl.	0.2	485	I.R., O.R. - Slightly Glazed	None	77.3
	342	M-1 (Rc 55) Stl.	0.6	497	I.R. - Glazed & Superficially Pitted O.R. - Glazed	None	77.3
E-42	337	M-1 (Rc 55) Stl.	<0.1	510	I.R., O.R., Balls - Smeared	I.R., O.R. Balls	77.8
	336	M-1 (Rc 55) Stl.	<0.1	485	I.R. - Superficially Pitted O.R. - Slightly Glazed	None	77.8
E-41	347	M-1 (Rc 55) Stl.	<0.1	505	None	None	79.6
	346(3)	M-1 (Rc 55) Stl.	0.2	500	I.R., O.R. - Glazed & Flaked	I.R., O.R.	79.6
E-44	339	M-1 (Rc 55) Stl.	<0.1	507	I.R., O.R. - Slightly Glazed	None	103.7
	338	M-1 (Rc 55) Stl.	<0.1	491	I.R. - Glazed & Flaked O.R. - Glazed Balls - 1 Flake	I.R., Ball	103.7
(4) E-39	333(2)	M-1 (Rc 55) Stl.	9.1	496	I.R. - Glazed & Flaked O.R. - Glazed	I.R.	161.3
	332	M-1 (Rc 55) Stl.	<0.1	479	I.R. - Glazed & Pulled O.R. - Slightly Glazed & Superficially Pitted	I.R.	161.3
(5) E-18	247	M-1 (Rc 55) Stl.	<0.1	495	None	None	216.0
	246	M-1 (Rc 55) Stl.	<0.1	504	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	216.0
E-20	252	M-1 (Rc 55) Stl.	<0.1	506	None	None	230.8
	251	M-1 (Rc 55) Stl.	<0.1	500	None	O.R.	230.8
E-21	254	M-1 (Rc 55)Stl.	<0.1	511	None, 1 Ball Flaked	Ball	231.1
	253	M-1 (Rc 55)Stl.	<0.1	505	None	None	231.1
E-17	244	M-1 (Rc 55)Stl.	<0.1	505	None	None	231.1
	243	M-1 (Rc 55)Stl.	<0.1	505	None	None	231.1
E-19	249	M-1 (Rc 55)Stl.	<0.1	496	None	None	231.1
	248	M-1 (Rc 55)Stl.	<0.1	475	None	None	231.1

(1) The M-1 (Rc 55) Steel Cages were silver plated on their bores as shown in Enclosure 16 of

(2) The inner race cage land riding surface of these bearings were worn excessively.

(3) The cages in these bearings had split circumferentially in two.

(4) In accordance with Rule 2 for endurance results (given in the Appendix), one bearing is considered a failure, the other is considered as a suspended test.

(5) Both bearings in this test were considered suspended tests because it was found that excessive coking had formed on the failed bearing during the normal weekend shutdown which contributed to its failure upon restart.

ENCLOSURE 14

ENDURANCE OF CVM M-1 STEEL BEARINGS (#455760)

Thrust Load - 580 Lbs. Speed - 42,800 rpm Lubricant - Esso Turbo Oil 35

Test Run No.	Bearing No.	Cage (1) Material	Cage (1) Bore Wear, Mils	Avg. Temp. °F	Lubrication Distressed Element(s)	Part(s) Failed	Life 10^6 Revs.
E-22	258	M-1 (Rc 55) Stl.	1.8	500	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	115.3
	257	M-1 (Rc 55) Stl.	<0.1	484	None	None	115.3

(1) The cages used in these bearings were silver plated in their bores as shown in Enclosure 16 of (1).

ENCLOSURE 15

ENDURANCE OF CVM M-1 STEEL 7205 BEARINGS (#455760) IN A N_2 ATMOSPHERE

Thrust Load = 459 Lbs. **Speed = 42,800 rpm** **Lubricant = Monsanto Skylube 600 (PWA 524)**

Test Run No.	Bearing No.	Cage (4) Material	Cage (4) Bore Wear, Mils	Avg. Temp. °F	Lubrication Distressed Element(s)	Part(s) Failed	Life 10^6 Revs.
(1) E-31	308	M-1 (Rc 55) Stl.	< 0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.15
	311	M-1 (Rc 55) Stl.	2.0	300	None	None	.03
(1) E-34	310	M-1 (Rc 55) Stl.	< 0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.05
	309	M-1 (Rc 55) Stl.	< 0.1	300	None	None	.05
(1) E-33	306	M-1 (Rc 55) Stl.	< 0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.08
	305	M-1 (Rc 55) Stl.	< 0.1	300	None	None	.08
(1) E-26	269	M-1 (Rc 55) Stl.	< 0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.13
	268(3)	M-1 (Rc 55) Stl.	< 0.1	300	None	None	.13
E-52	255(3)	M-1 (Rc 55) Stl.	0.1	500	I.R., O.R. Balls - Smeared	I.R., O.R., Balls	.26
	259(3)	M-1 (Rc 55) Stl.	0.1	473	None	None	.26
(1) E-27	303	M-1 (Rc 55) Stl.	2.0	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.26
	268(3)	M-1 (Rc 55) Stl.	0.5	300	None	None	.26
E-29	270(2)	M-1 (Rc 55) Stl.	< 0.1	466	I.R., O.R. - Glazed & Flaked	I.R., O.R.	1.74
	304(3)	M-1 (Rc 55) Stl.	< 0.1	426	None	None	.59
E-24	263(3)	M-1 (Rc 55) Stl.	< 0.1	428	None	None	.77
	262	M-1 (Rc 55) Stl.	< 0.1	518	I.R., O.R. - Superficially Pitted	None	.77
E-30	313	M-1 (Rc 55) Stl.	< 0.1	506	None	None	1.03
	304(3)	M-1 (Rc 55) Stl.	0.8	504	I.R. - Glazed & Flaked O.R. - Glazed	I.R.	1.03
E-25	263(3)	M-1 (Rc 55) Stl.	4.5	408	I.R., O.R. - Superficially Pitted	None	1.15
	264	M-1 (Rc 55) Stl.	2.3	500	I.R. - Glazed & Flaked O.R. - Glazed & Superficially Pitted	I.R.	1.15
E-28	302	M-1 (Rc 55) Stl.	< 0.1	476	None	None	2.57
	301(5)	M-1 (Rc 55) Stl.	35.0	561	I.R., O.R. - Glazed & Flaked Balls - 2 Flaked	I.R., O.R., Balls	2.57
E-32	259 (3)	M-1 (Rc 55) Stl.	< 0.1	543	I.R. - Glazed O.R. - Glazed & Superficially Pitted	None	5.14
	307	M-1 (Rc 55) Stl.	< 0.1	541	I.R., O.R. - Slightly Glazed	None	5.14
E-23	261	M-1 (Rc 55) Stl.	0.2	595	None	None	98.6
	260(5)	M-1 (Rc 55) Stl.	89.3	587	I.R. - Flaked O.R. - Glazed Balls - 1 Flaked	I.R., Balls	98.6

(1) Average bearing temperatures for this run were estimated to be 300°F since actual temperatures were not obtained due to short test duration.

(2) The test life of this bearing differs from its companion bearing because it had been run previously in an aborted test. Its accumulated test life has been used for maximum likelihood estimates.

(3) As shown above, this bearing has been run in two tests; therefore, its accumulated test life has been used for maximum likelihood estimates.

(4) The cages were silver plated in their bores as shown in Enclosure 16 of Reference (1).

(5) The inner race cage land riding surfaces of this bearing was worn excessively.

ENCLOSURE 16

ENDURANCE RESULTS OF CVM M-1 STEEL 7205 BEARINGS (#455760) IN A N_2 ATMOSPHERE

Thrust Load = 365 lbs. Speed = 42,800 rpm Lubricant = Monsanto Skylube 600 (PWA 524)

Test Run No.	Bearing No.	Cage Material (3)	Cage Bore Wear, Mils	Avg. Temp. °F	Lubrication Distressed Element(s)	Part(s) Failed	Life 10^6 Revs.
(1) E50	324	M-1 (Rc 55)Stl.	<0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.03
	323	M-1 (Rc 55)Stl.	<0.1	300	None	None	.03
(1) E49	320	M-1 (Rc 55)Stl.	<0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.08
	(2) 311	M-1 (Rc 55)Stl.	0.2	300	None	None	.11
E51	(2) 305	M-1 (Rc 55)Stl.	0.5	481	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	1.36
	321	M-1 (Rc 55)Stl.	3.6	479	I.R., O.R. - Slightly Glazed	None	1.28

(1) Average bearing temperatures for this run were estimated to be 300°F, since actual temperatures were not obtained due to short test duration.

(2) This bearing had been run previously in tests conducted with the same lubricant and at the same speed and temperature except at a higher thrust load (459 lbs.). Since the higher thrust load has a more pronounced effect on the bearing's test life, its accumulated test life under both load conditions has been considered for the maximum likelihood analysis for this bearing group.

(3) The cages were silver plated in their bores as shown in Enclosure 16 of (1).

ENCLOSURE 17

ENDURANCE OF CVM M-1 STEEL 7205 BEARINGS (#455760) IN AIR

Thrust Load - 459 Lbs. Speed - 42,800 rpm Lubricant - Monsanto Skylube 600 (PWA 524)

Test Run No.	Bearing No.	Cage (1) Material	Cage (1) Bore Wear, Mils	Avg. Temp. °F	Lubrication Distressed Element(s)	Part(s) Failed	Life 10^6 Revs.
E-46	357	M-1 (Rc 55) Stl.	<0.1	275	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.05
	356	M-1 (Rc 55) Stl.	<0.1	326	None	None	.05
E-45 (2)	352	M-1 (Rc 55) Stl.	<0.1	300	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	.08
	351	M-1 (Rc 55) Stl.	<0.1	300	None	None	.08
E-47 (3)	350	M-1 (Rc 55) Stl.	0.4	600	I.R. - Slightly Glazed Balls - 2 Flaked	Balls	76.3
	348	M-1 (Rc 55) Stl.	78.4	560	None	None	76.3
E-48 (4)	354	M-1 (Rc 55) Stl.	0.2/0.3	590	I.R. - Smeared O.R. - Slightly smeared & superficially pitted Balls - Smeared	I.R., O.R., Balls	189.3
	353	M-1 (Rc 55) Stl.	0.5/0.3	572	I.R. - Slightly Glazed O.R. - Slightly Glazed and fragment dented	None	189.3

(1) The cages were silver plated in their bores as shown in Enclosure 16 of (1).

(2) Average bearing temperatures for this run were estimated to be 300°F since actual temperatures were not obtained due to short test duration.

(3) This test was conducted as follows:

The initial 6.7 hours with N_2 sealing the load plug clearance.
The remaining 23.0 hours in air.

(4) The cage bore wear for the bearings used in this test is given first for the original cage which ran 171.5 x 10^6 revs. and then their replacement which ran for 17.8 x 10^6 revs.

ENCLOSURE 18

ENDURANCE OF CVM M-1 STEEL 7205 BEARINGS (#455760)

Thrust Load - 459 Lbs. Speed - 42,800 rpm Lubricant - Socony XRM-109F-1

Test Run No.	Bearing No.	Cage (1) Material	Cage (1) Bore Wear, Mils	Avg. Temp. °F	Lubrication Distressed Element(s)	Part(s) Failed	Life 10^6 Revs.
E-55	363	M-1 (Rc 55) Stl.	<0.1	540	* None	None	2.2
	362	M-1 (Rc 55) Stl.	3.6	517	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	2.2
E-57	369	M-1 (Rc 55) Stl.	<0.1	506	None	None	2.4
	368	M-1 (Rc 55) Stl.	<0.1	490	I.R., O.R., Glazed - Superficial pulling Balls - Slightly smeared	None	2.4
E-54	359	M-1 (Rc 55) Stl.	0.5	533	I.R. - Superficial pulling O.R. - Slightly glazed	None	3.0
	358 (2) (3)	M-1 (Rc 55) Stl.	>1.0	524	I.R., O.R., Balls - Smeared	I.R., O.R., Balls	3.0
E-56	361	M-1 (Rc 55) Stl.	1.2	598	None	None	8.5
	362 (3)	M-1 (Rc 55) Stl.	1.6	567	I.R., O.R. - Glazed - Superficial pulling Ball - Slightly Smeared	None	8.5
E-53	355	M-1 (Rc 55) Stl.	3.3	536	I.R., O.R., Glazed & Flaked	I.R., O.R.	17.5
	344	M-1 (Rc 55) Stl.	1.4	563	None	None	17.5

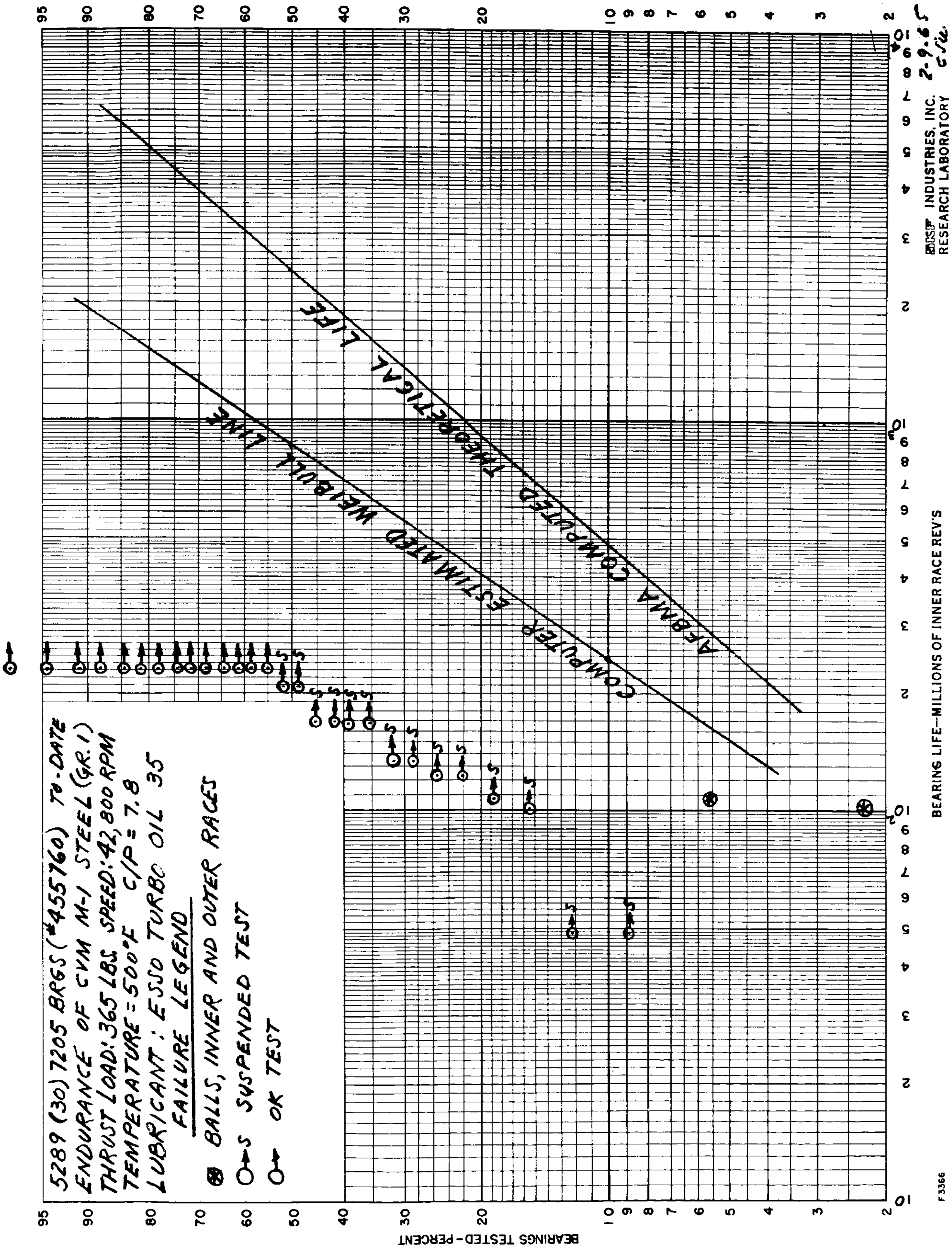
(1) The cages were silver plated in their bores as shown in Enclosure 16 of (1).

(2) The inner race cage land riding surfaces of this bearing was worn.

(3) The cage for this bearing split circumferentially in two and shattered.

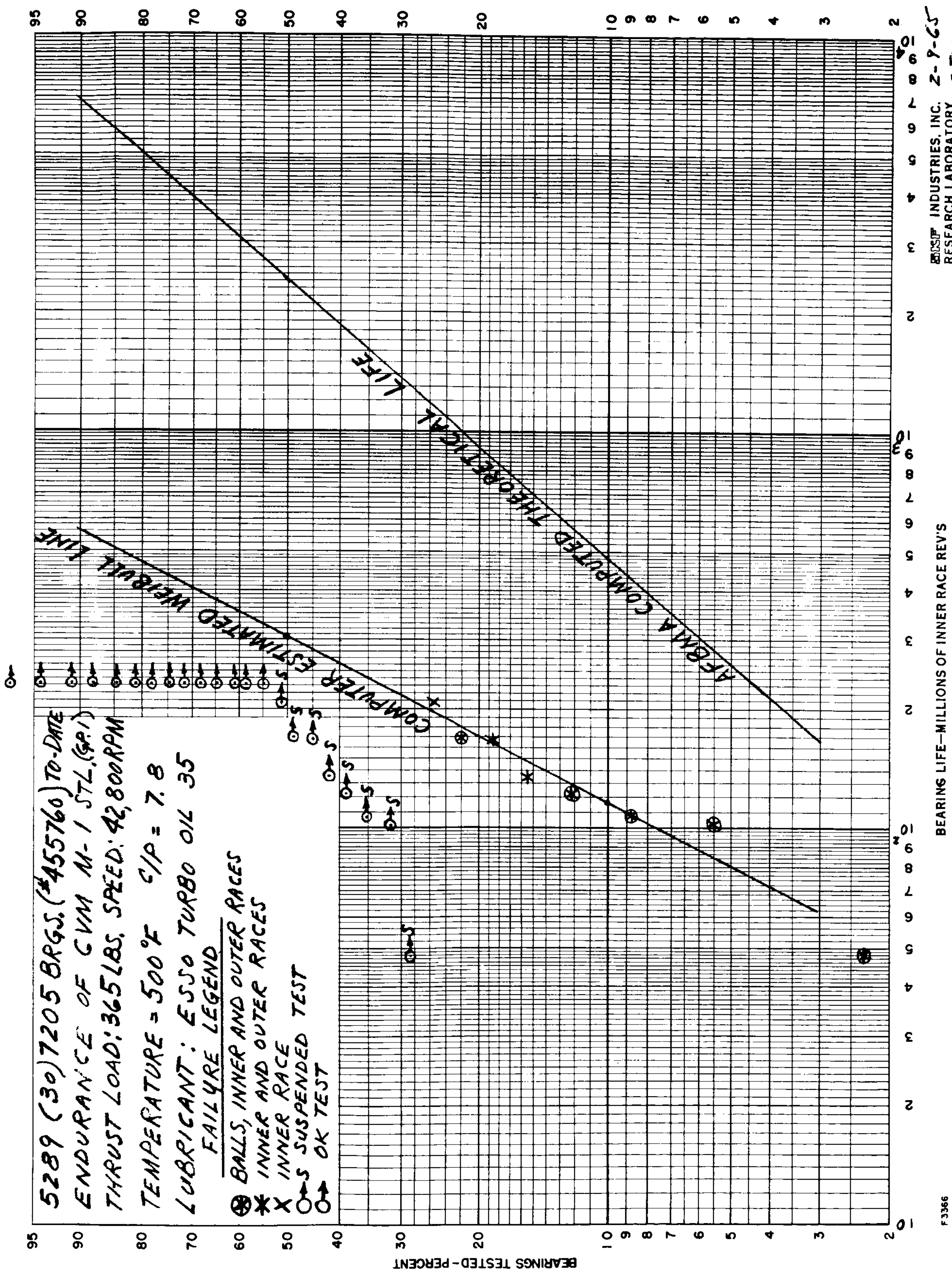
ENCLOSURE 19

WEIBULL PLOT OF CVM M-1 BEARINGS (SMEARING FAILURES ONLY)
AT C/P = 7.8 WITH TURBO OIL 35



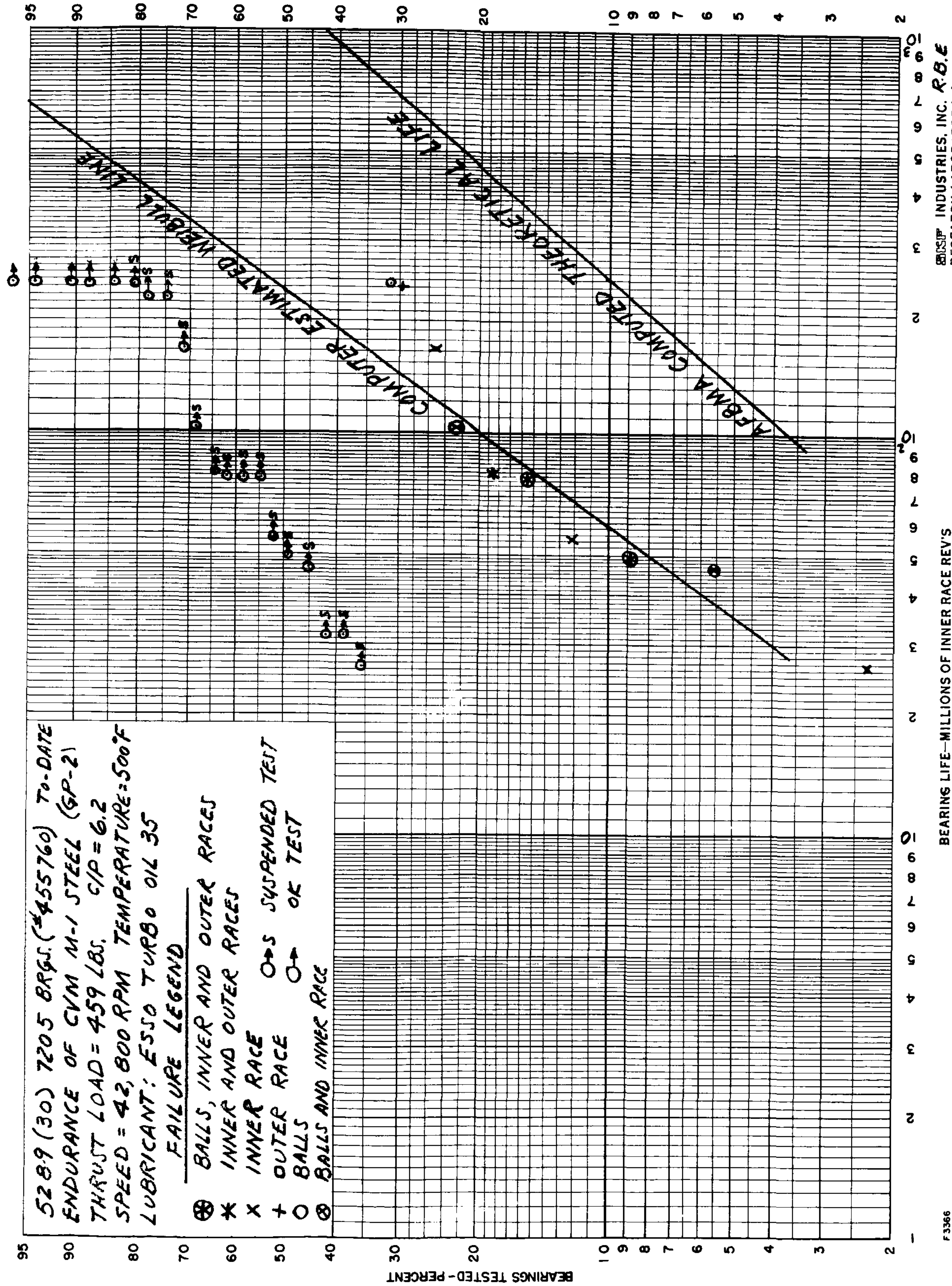
ENCLOSURE 20

WEIBULL PLOT OF CVM M-1 BEARINGS (ALL FAILURES) AT C/P = 7.8 WITH TURBO OIL 35



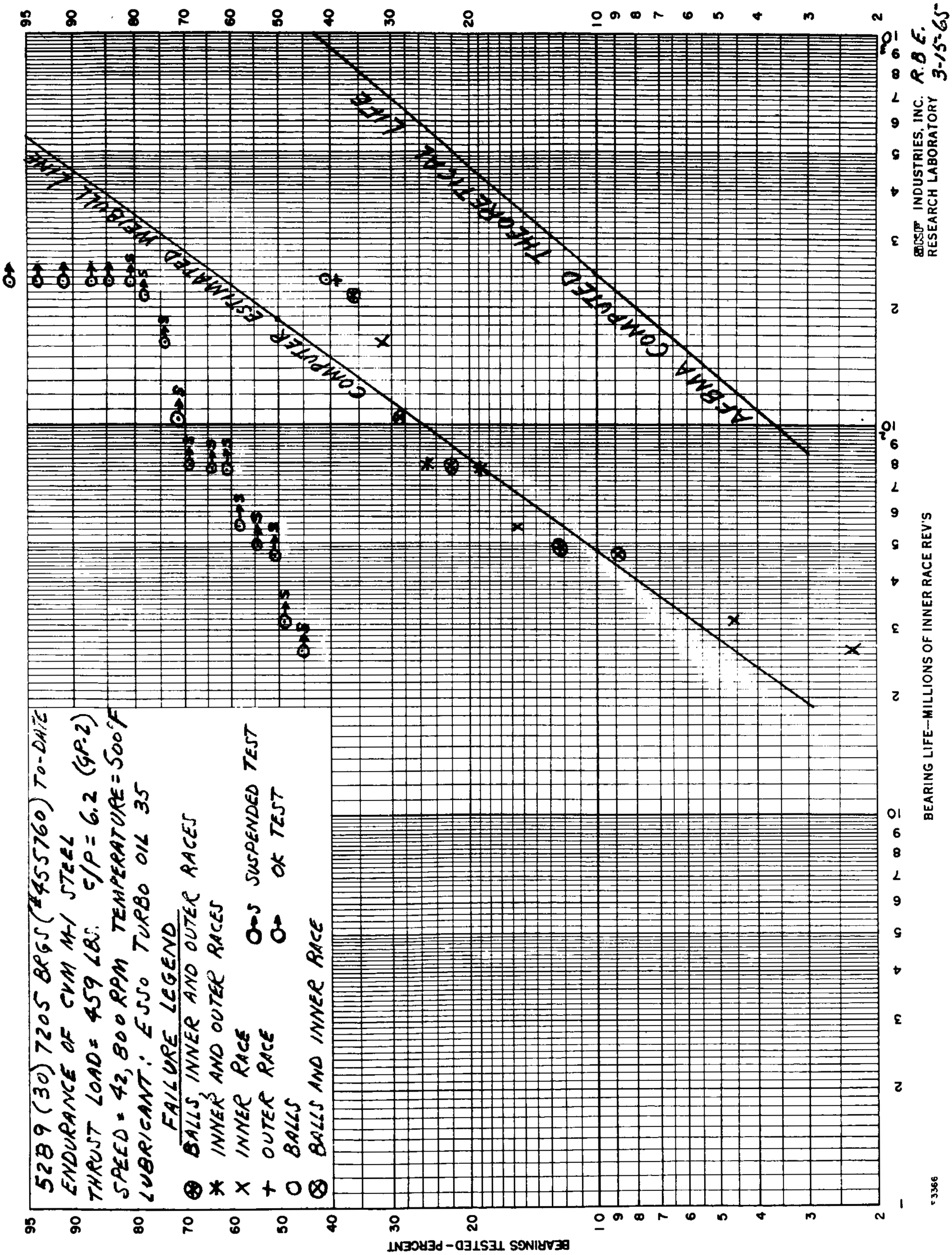
ENCLOSURE 21

WEIBULL PLOT OF CVM M-1 BEARINGS (SMEARING & FLAKING FAILURES ONLY) AT C/P = 6.2 WITH TURBO OIL 35



ENCLOSURE 22

WEIBULL PLOT OF CVM M-1 BEARINGS (ALL FAILURES)
AT C/P = 6.2 WITH TURBO OIL 35



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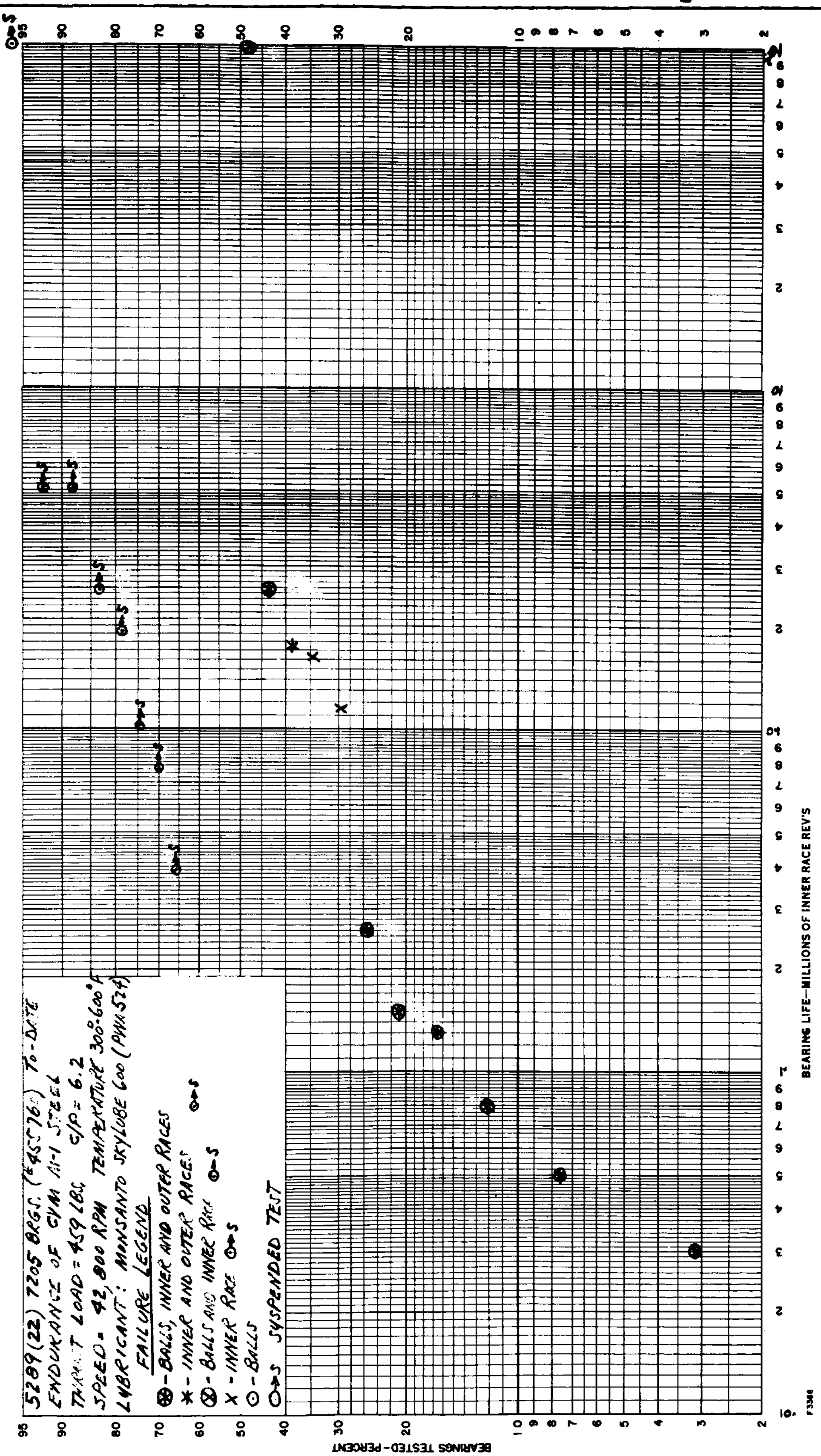
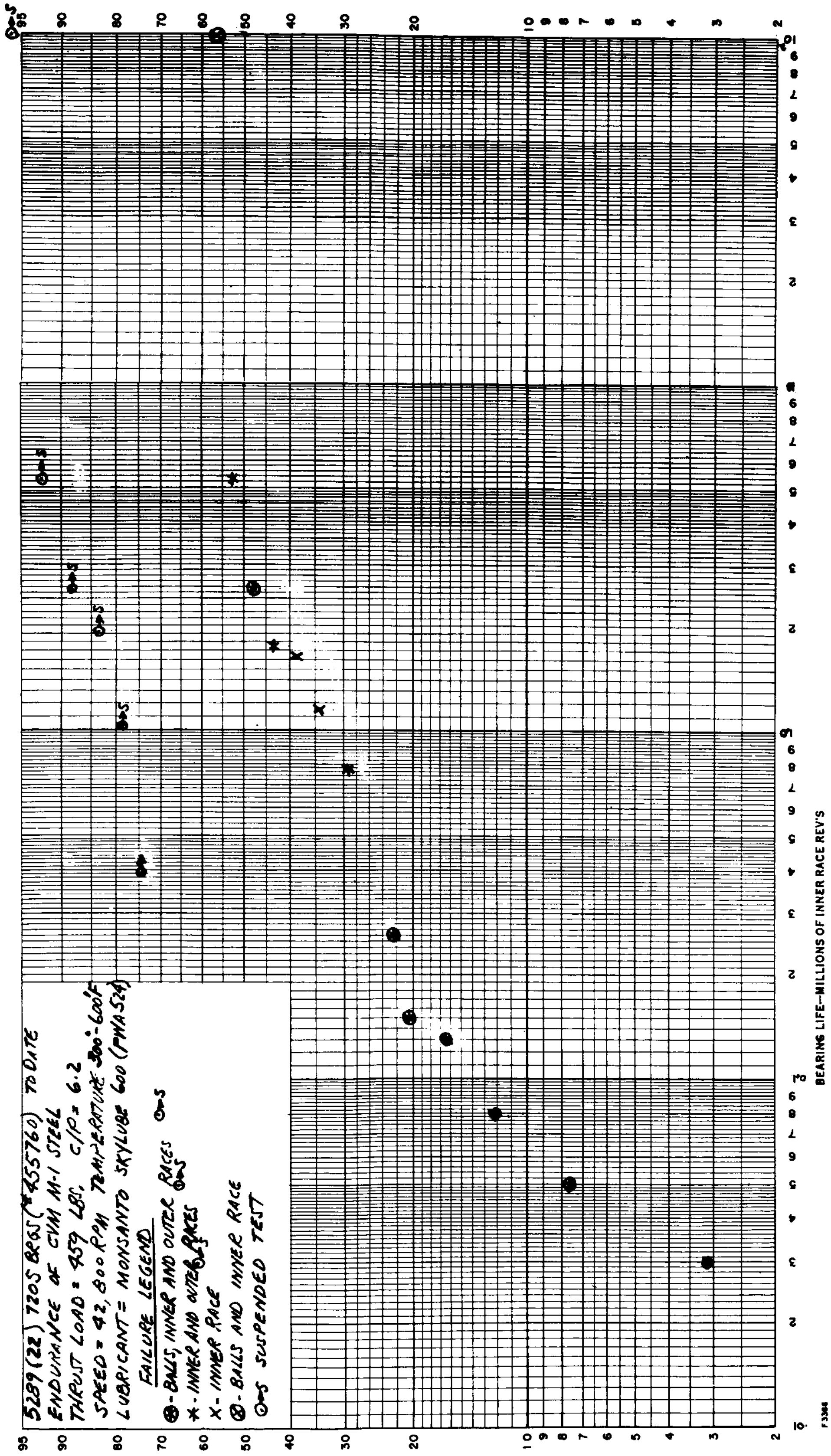
ENCLOSURE 23

WEIBULL PLOT OF CVM M-1 BEARINGS (SMEARED AND FLAKING FAILURES ONLY) AT C/P = 6.2 WITH SKYLUBE 600 (PWA 524) IN N_2 ATMOSPHERE



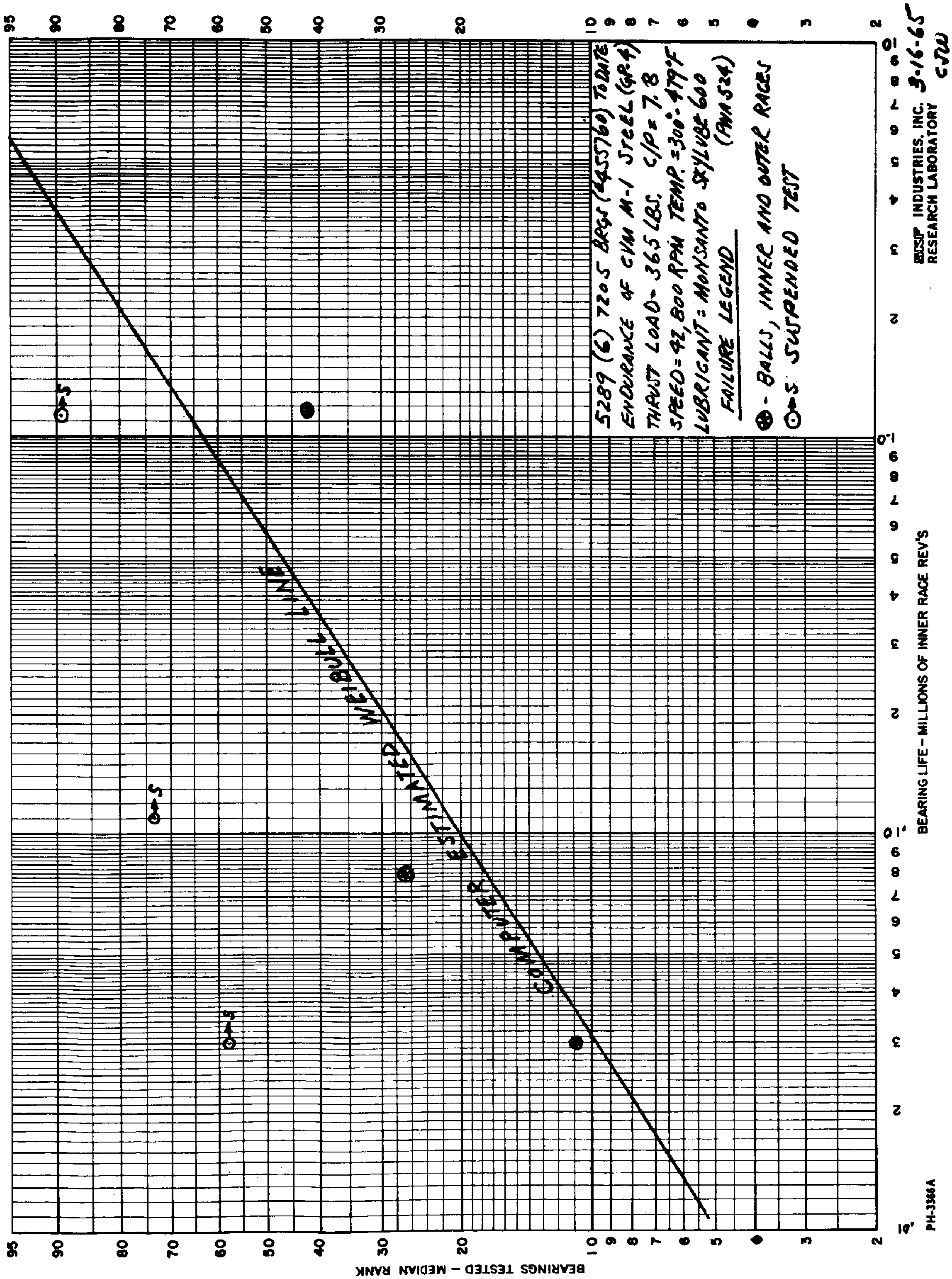
ENCLOSURE 24

WEIBULL PLOT OF CVM M-1 BEARINGS (ALL FAILURES) AT C/P = 6.2 WITH SKYLUBE 600 (PWA 524) IN N_2 ATMOSPHERE



ENCLOSURE 25

WEIBULL PLOT OF CVM M-1 BEARINGS (ALL FAILURES)
AT C/P = 7.8 WITH SKYLUBE 600 (PWA 524) IN N_2 ATMOSPHERE



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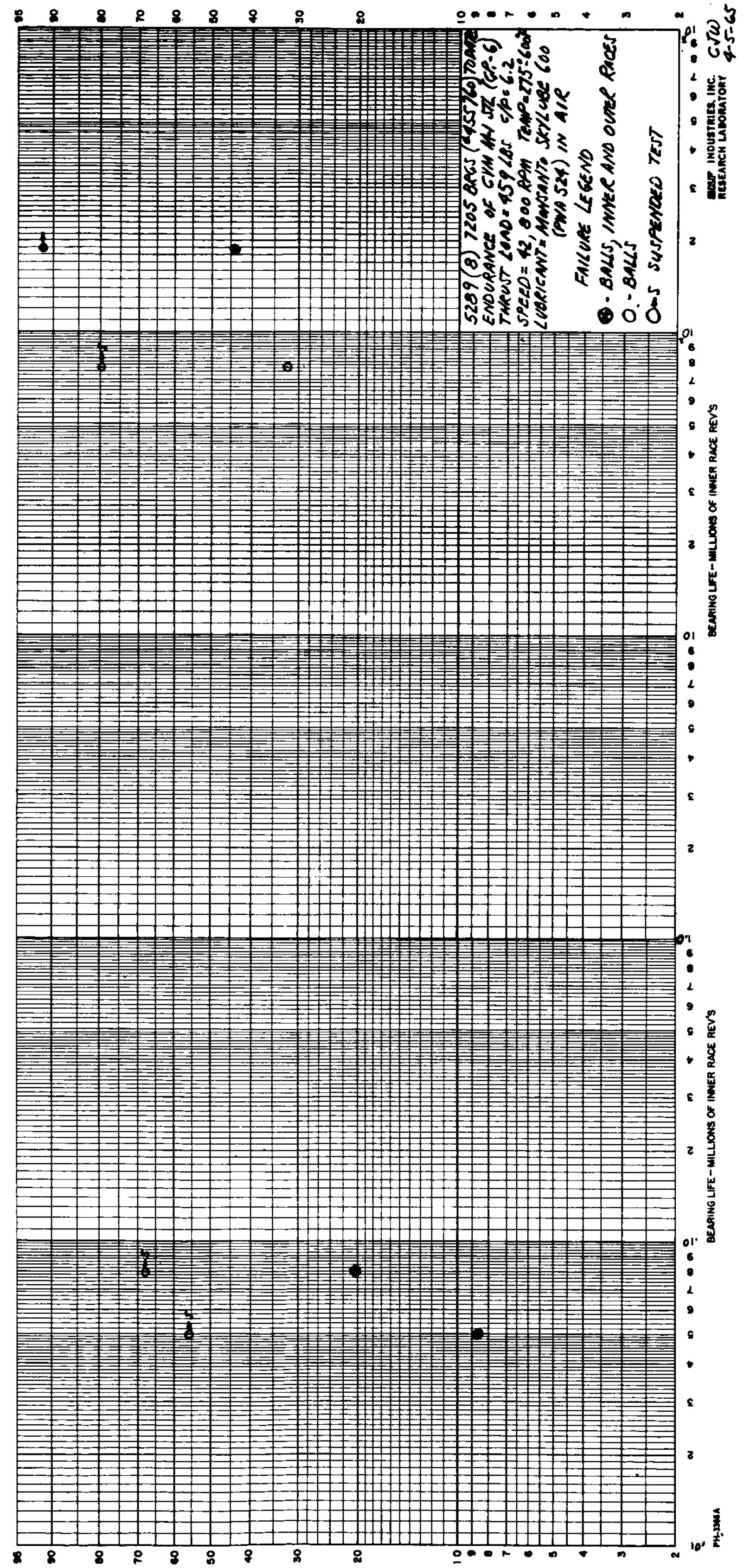
ENCLOSURE 26

WEIBULL PLOT OF CVM M-1 BEARINGS (ALL FAILURES) AT C/P = 6.2 WITH SKYLUBE 600 (PWA 524) IN AIR



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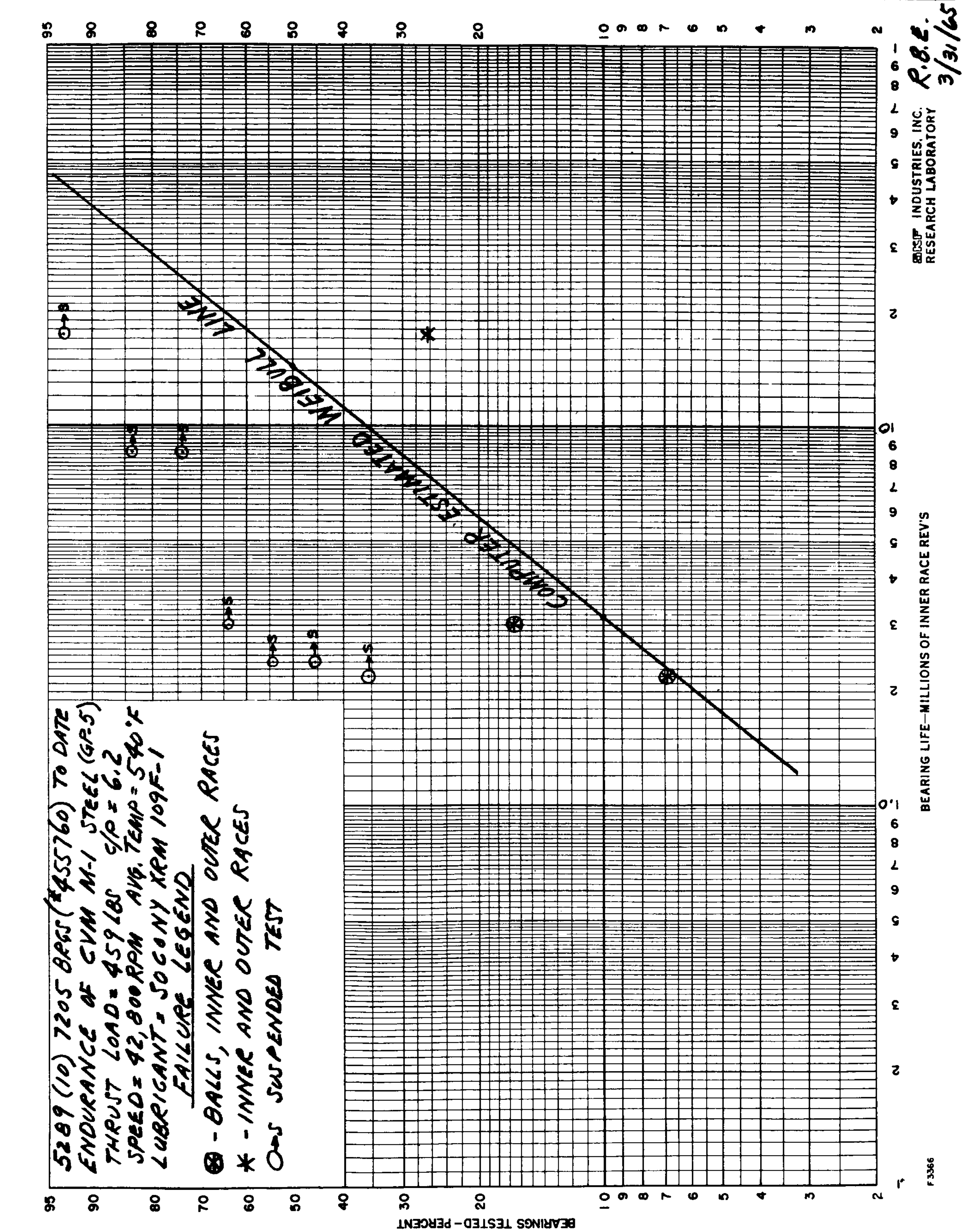
ENCLOSURE 27

WEIBULL PLOT OF CVM M-1 BEARINGS (SMEARING AND FLAKING FAILURES ONLY) AT C/P = 6.2 WITH XRM 109F-1



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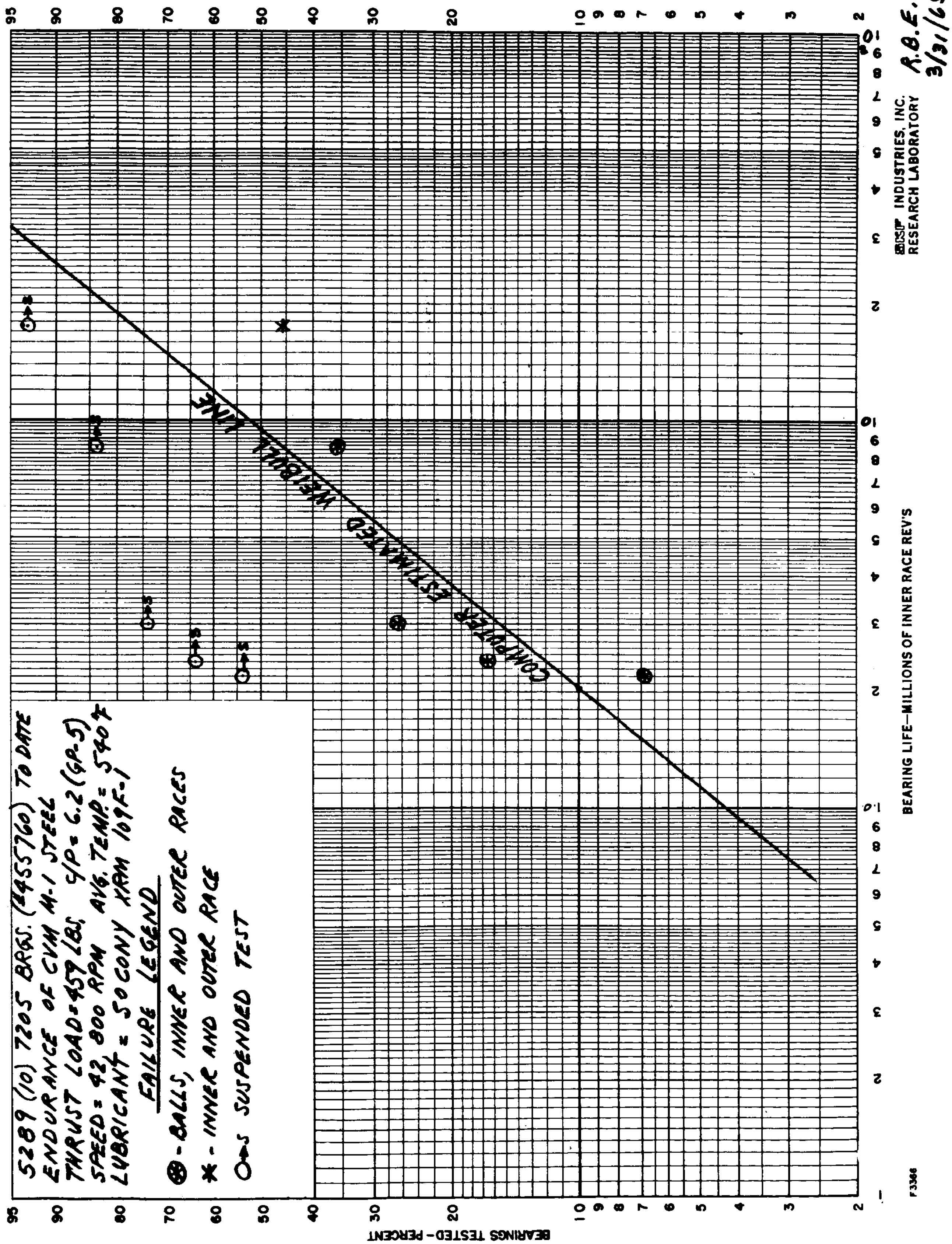
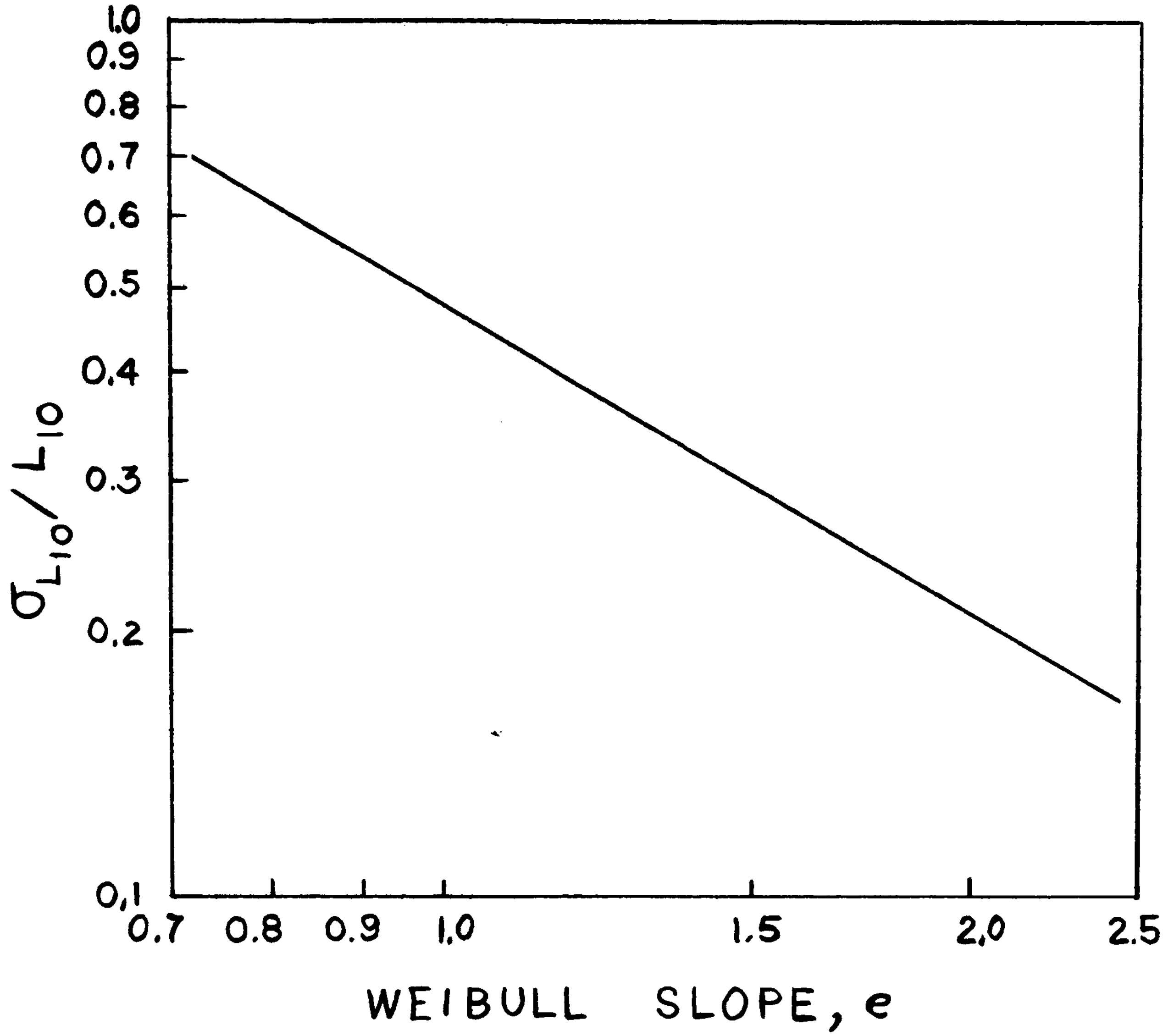
ENCLOSURE 28

WEIBULL PLOT OF CVM M-1 BEARINGS (ALL FAILURES)
AT C/P = 6.2 WITH XRM 109F-1



ENCLOSURE 29



STANDARD ERROR OF MAXIMUM LIKELIHOOD ESTIMATES OF L_{10} FROM A TRUNCATED SAMPLE OF SIZE 30